Thesis for the degree of Licentiate of Engineering

Weighing the Value of Bioenergy

Accounting for Land Carbon and the Timing of Emissions

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Division of Physical Resource Theory

Chalmers University of Technology
Göteborg, Sweden 2026

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Acknowledgements, dedications, and similar personal statements in this thesis reflect the author's own views.

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Cover: a beam balance weighing a standing forest, roots and soil included, against a stack of cut logs.
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Abstract

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EU accounting and most energy-system models treat bioenergy as carbon neutral at the point of combustion, yet harvesting biomass reduces the carbon held in the land. This thesis asks, across three linked studies, what bioenergy is worth to a carbon-neutral European energy system once those land carbon stock changes are counted.

Paper III derives a welfare-consistent rate for weighting CO_2 emitted in different years, in place of the discount rates and time horizons that carbon accounting fixes by convention. Expert-elicited normative parameters and probabilistic climate–economy pathways give a median rate of 0.60% per year (0.31% under expected-welfare aggregation), far below the social discount rate because rising marginal damages offset most of the discounting. The variation is driven mainly by normative choices rather than empirical uncertainty about growth or warming.

Paper II applies the CO_2 weighting rate within ClimFor, a mass-balanced model tracking carbon from forest growth through harvest, processing, use, and disposal, across some 40 EU wood products. Against a no-harvest counterfactual, the EU forestry and wood sector is a net climate cost of roughly 165 Mt CO_2 eq per year – not the sink assumed in policy and life-cycle assessment – and stays a net source under every baseline, weighting and substitution treatment tested.

Paper I supplies the resulting emission factors to the energy-system model PyPSA-Eur. Internalizing them cuts cost-optimal biomass use by 52%, driving stemwood and its residues from the mix as wind and solar expand in their place.

Keywords: bioenergy, carbon stock changes, forest carbon, wood products, emission factors, time-weighting of CO_2, social cost of carbon, life-cycle assessment, energy system modelling, EU climate policy

List of Publications

This thesis is based on the following appended papers:

Paper I **Renzelmann, T.**, Reichenberg, L., Wirsenius, S., Hedenus, F. (2026). *Reassessing the Value of Bioenergy: Carbon Stock Changes Matter.* Manuscript.

Paper II

Wirsenius, S., **Renzelmann, T.** (2026). *The climate cost of wood products including substitution benefits.* Manuscript.

Paper III

Renzelmann, T., Johansson, D. J. A., Persson, U. M., Reichenberg, L. (2026). *Weighting Emissions and Removals over Time: Introducing WE–CO_2 and a Welfare-Equivalent CO_2 Weighting Rate.* Manuscript.

The paper are manuscripts and work in progress. Their supplementary information is available from the author.

Author’s Contributions

Contributions to the appended papers follow the CRediT taxonomy (ANSI/NISO Z39.104-2022), which asks that all fourteen roles be used to present author contributions. An em dash marks a role that did not arise. Initials: T.R. Renzelmann; L.R. Reichenberg; S.W. Wirsenius; F.H. Hedenus; D.J. Johansson; M.P. Persson.

Role	Paper I	Paper II	Paper III
Conceptualization	T.R., L.R., F.H.	S.W.	T.R., D.J., M.P.
Data curation	T.R.	S.W., T.R.	T.R.
Formal analysis	T.R.	S.W., T.R.	T.R.
Funding acquisition	L.R., F.H.	S.W., L.R., F.H.	L.R., F.H.
Investigation	T.R., L.R.	S.W., T.R.	T.R.
Methodology	T.R., L.R., S.W.	S.W., T.R.	T.R., D.J., M.P.
Project administration	L.R.	S.W.	L.R.
Resources	—	—	—
Software	T.R.	S.W.	T.R.
Supervision	L.R.	S.W.	L.R.
Validation	—	—	—
Visualization	T.R., L.R.	S.W.	T.R.
Writing – original draft	T.R.	S.W.	T.R.
Writing – review & editing	all authors	S.W., T.R.	all authors

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When I applied for the PhD position here at Chalmers, I was unsure whether I actually wanted to move to Gothenburg and take it. Visiting the division in person and meeting the people who would become my colleagues finally convinced me. I have not regretted it since, and I enjoy coming to work largely because of the people of FRT.

This thesis would not have been possible without the expert and caring supervision of Lina Reichenberg. Lina, I enjoy our discussions and brainstorming sessions, and I am grateful for the support, the encouragement, and the freedom you give me. Thank you!

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Martin Persson and Daniel Johansson, thank you for seeing potential in my idea on welfare-equivalent CO_2 and for making time to turn it into a paper. It is a privilege to learn from your experience and your ideas, and working with you is a lot of fun.

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This work would have been far harder without the open-source energy modelling community, and the developers of PyPSA-Eur in particular.

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Beyond the work itself, I would like to thank all my friends at Chalmers and elsewhere for their love and support, and especially my family, for always being there throughout this journey.

Timon Renzelmann
Göteborg, 2026

Use of AI

The rapid advancement of capable AI has transformed how research is conducted, and it has shaped both my daily work and this thesis. Thanks to AI I was able to write code faster and more proficiently than I could have on my own, which in turn influenced how I analysed and visualized my data. I outsourced practical annoyances such as formatting documents, including LaTeX figures and tables – chores I do not think anybody will miss doing manually. AI also helped me conduct rapid literature sweeps to check whether certain claims held or required adjustment.

The fuller truth, however, is that my use of AI was much more deeply integrated into my workflow than just superficial coding and formatting. I discussed concepts with reasoning models, and let AI read and critique my drafts or shorten longer texts. To some extent, it served as a digital coworker that I benefited from in many aspects of the research process.

Despite this extensive use, I did not outsource my critical thinking. AI wrote code that I ran and checked, but it did not decide what to model, which data to use, or what the results mean; those choices are my own and my co-authors'. I constantly questioned the claims the AI made during our chats, checked the literature it suggested against the primary sources before citing it, and used the technology to augment (rather than replace) the intellectual heavy lifting required to bring forth new ideas and discuss results. I take full responsibility for the content, errors included.

Contents

Abbreviations

ALCA	Attributional life cycle assessment
CCS	Carbon capture and storage
ClimFor	Forest and wood-product carbon model (Paper II)
CLCA	Consequential life cycle assessment
CSC	Carbon stock change
DF	Displacement factor
ETS	Emissions Trading System
EU	European Union
GDP	Gross domestic product
GTP	Global Temperature change Potential
GWP	Global Warming Potential
IAM	Integrated assessment model
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
LCA	Life cycle assessment
LULUCF	Land use, land-use change and forestry
MGA	Modelling to generate alternatives
PyPSA-Eur	Python for Power System Analysis – Europe (Paper I)
RED	Renewable Energy Directive (European Union)
RFF-SP	Resources for the Future Socioeconomic Projections
RFS	Renewable Fuel Standard (United States)
SCC	Social cost of carbon
WE–CO_2	Welfare-equivalent CO_2 (Paper III)

Chapter 1

Introduction

Climate change causes harm, and mitigating it is worthwhile because doing so improves the lives of humans and non-human animals on this planet. This holds true regardless of any national or regional climate targets, policies, or historic developments, which are the more common entry point for research in my field. Questions surrounding bioenergy and carbon emissions are, as I will show, practical problems within that larger pursuit of well-being.

As the energy system accounts for roughly three-quarters of global greenhouse gas emissions (Climate Watch 2024), its transformation is a prerequisite for climate change mitigation and for securing a sustainable and liveable future (IPCC 2023).

Within this challenge, bioenergy stands out as a linchpin of many transformation strategies. It promises versatile energy (Millinger et al. 2025; Lauer et al. 2023) that can help balance the intermittent supply of variable renewables to provide heat, electricity (Johansson et al. 2019; Millinger et al. 2022; Zeyen et al. 2021) and carbon-neutral fuels essential for hard-to-electrify sectors such as aviation or shipping (Mandova et al. 2019; Tanzer et al. 2020).

The carbon neutrality often assumed for bioenergy, however, does not hold once the carbon dynamics of biomass production are accounted for. Harvesting biomass alters land carbon stocks – the carbon held in living and dead biomass and in the soil – and can therefore generate substantial upstream carbon stock changes (CSCs) (Searchinger et al. 2018b; Searchinger et al. 2022; Fargione et al. 2008). These can be permanent losses, such as after disruptive land-use changes like deforestation and agricultural expansion (*lost* carbon storage) (Fargione et al. 2008), or dynamic effects that persist while the land remains in use (*forgone* carbon storage) (Fehrenbach and Bürck 2022). A market-level counterargument holds that stronger biomass demand raises forest carbon stocks over time, by inducing afforestation and more intensive management (Favero et al. 2020).

Despite these impacts, energy system optimization models conventionally treat bioenergy as carbon neutral (Millinger et al. 2022; Millinger et al. 2025; Pickering et al. 2022), and much of the systemic value they attribute to it rests on that very assumption. European Union (EU) accounting follows the same convention. The CO_2 released when biomass is burned is recorded in the land-use sector rather than the energy sector, so bioenergy enters energy-sector accounts as carbon-neutral at the point of combustion (Booth and Giuntoli 2025). Ignoring these land carbon impacts can inflate the apparent role of bioenergy in a climate-efficient energy system.

Beyond this missing representation of biomass's CSCs in energy models, the quantification of these impacts has so far also remained limited. Where forest-carbon effects are quantified at all, the estimates rest on coarse and inconsistent foundations. Most assessments retain the biogenic-neutrality convention or apply fixed emission coefficients that omit the forgone forest carbon sink, and the few that do model it treat forest dynamics and product substitution separately rather than within one mass-balanced framework (Cherubini and Strømman 2011; Røyne et al. 2016; Myllyviita et al. 2021; Fehrenbach et al. 2022; Soimakallio et al. 2016).

To be able to collapse a time series of CSCs into single emission factors that could be used in energy system models, they need to be weighted over time. If an emission now and an emission later are not equivalent, quantifying the difference requires a stated basis, as does the alternative position that they should be assigned equal weight. In carbon accounting practice, the weighting applied across years is not derived from the changing damages that differently timed emissions incur. Researchers instead apply discount rates (Searchinger et al. 2018b; Peng et al. 2023) or time horizons (Brandão et al. 2013) chosen by convention, whose relation to the evolving welfare impacts of emissions is not defined. Restoring that relation is where this thesis begins. It derives the weighting from what makes mitigation worthwhile in the first place, the harm that emissions cause.

1.1 Aims

This thesis aims to create a better understanding of the value of bioenergy for a carbon-neutral European energy system, accounting for the land carbon dynamics of biomass production. Value is understood here broadly, as the role bioenergy plays within a cost-optimal energy system – which feedstocks are used, in what quantities, in which sectors, and what each is worth at the margin. Reaching this requires answering several related research questions, which I address through three papers.

Each of these questions depends on the answer to another (Figure 1.1). Assessing the value of bioenergy requires the emission intensity of each biomass feedstock. Obtaining that intensity requires expressing decades-long CSCs as

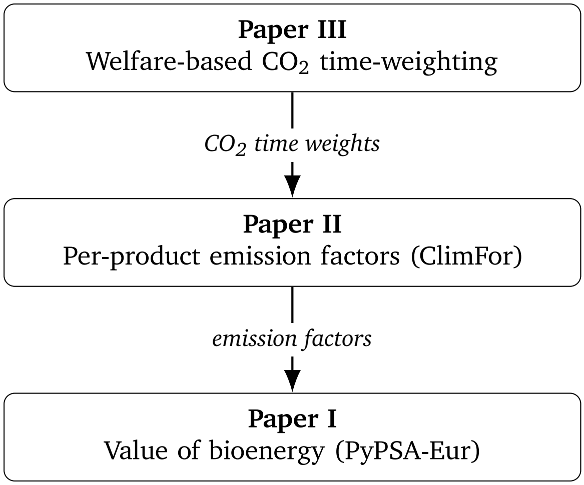


Figure 1.1: Flow of data between the three appended papers. Paper III provides the CO_2 time-weighting schedule that Paper II uses to collapse CSC trajectories into per-product emission factors, which Paper I in turn feeds into an energy-system model. The motivating questions run in the opposite direction, from the value of bioenergy to the weighting it depends on.

single emission factors, which in turn requires a defensible basis for weighting CO_2 emitted in different years. The papers are introduced below in the reverse order, the order in which they were built, each handing its result to the next.

Paper III provides a welfare-consistent basis for weighting emissions over time, deriving the rate from how the welfare impact of a tonne of CO_2 changes over the coming century.

Paper II applies that weighting to real carbon dynamics. It quantifies the climate impact of producing biomass across a diverse set of European feedstocks in unprecedented detail, combining forest and product carbon dynamics with Paper III's weights to express each wood product as a single emission factor.

Paper I puts those emission factors to work. It embeds them in a tailored, up-to-date energy-system optimization model (PyPSA-Eur) with a diversified set of biomass feedstocks and returns a revised picture of the role of bioenergy once its climate impact is accounted for at the point of decision.

1.2 Thesis structure

The remainder of this thesis proceeds in four chapters. The background sets the scene for bioenergy in the European Union and identifies the research gaps that motivate Papers I, II, and III. The methodology then introduces the three modelling tools on which the papers rest. The results chapter presents the key findings of the three papers, and the discussion places them in context, sets out the main contributions, and gives an outlook on future research.

Because the papers depend on one another, each chapter enters this chain at whichever point suits it. The numbering is a label rather than a reading order.

Chapter 2

Background

The climate value of biomass rests on the answers to three linked questions. The first is physical: how much less carbon the forest holds because of a harvest, and for how long. Harvesting wood today changes the forest carbon stock for decades (Helin et al. 2016), so the climate consequence of a single act of harvest is not a number but a time profile. The second is a question of weighting: any single figure assigned to such a profile – an emission factor, a displacement credit, a "carbon-neutral" label – is the product of an implicit choice about how to weight it over time. The third is systemic: where, given those weighted carbon consequences, biomass is best used in an economy that aims to curb emissions.

This chapter provides the grounding those answers require. It sets out how biomass and its governance work, reviews the research that surrounds it, and brings into view the controversies that remain unsettled.

2.1 Forests, carbon, and the climate system

The case for treating biomass as climate-neutral rests on a physical claim: that the CO_2 released when biomass is burnt or decays was only recently drawn from the atmosphere as the plant grew, so that over a full cycle of growth and harvest the net exchange with the atmosphere is zero (Cherubini and Strømman 2011). The extent to which this view holds depends on two questions, one physical and one largely normative. The first is the extent to which the carbon released by burning biomass, such as wood, is actually recovered. The second is the extent to which we care about the delay of this recovery – after all, it takes time for a new tree to grow, and in the interim, the carbon stored in the forest is lowered. In particular, carbon is extracted from the land at harvest, is recovered, often partially, during regrowth, while the harvested carbon finds its way (at different speeds depending on its use) to the atmosphere.

This section examines that time series in four parts. It covers the biophysics of the harvest debt (Section 2.1.1), product fate and substitution (Section 2.1.2), the forest-carbon and life-cycle models used to quantify it and their limitations (Section 2.1.3), and the gap that Paper II fills (Section 2.1.4).

2.1.1 Forest carbon and the harvest debt

A forest holds carbon in several distinct pools. In 2020 the world's forests stored about 870 Pg C in total, with roughly 45% in soils, 43% in living biomass above and below ground, 8% in deadwood, and 4% in litter (Pan et al. 2024).

How long that carbon stays stored depends on the rate at which it moves through these pools. A pool's *turnover time* is its stock divided by the flux passing through it. At steady state, it is equivalent to the mean time a carbon atom resides in a stock before moving on.

Turning over is not the same as returning to the atmosphere. Carbon shed from foliage falls as litter and carbon lost from fine roots enters the soil. At each step, only part is released as CO_2 while the rest is handed on to a slower pool. Because the fast pools continually feed the slow ones, an intact forest retains carbon far longer than the brisk turnover of leaves or fine roots alone would suggest. When taken over vegetation and soil together, from photosynthetic fixation to eventual release as CO_2, the mean residence time of carbon is about 23 years globally. This varies strongly with climate, ranging from roughly 15 years in the warm, fast-decomposing tropics to as much as 255 years in cold high-latitude soils (Carvalhais et al. 2014).

Felling removes much of the standing biomass, and the loss of that carbon from the forest is the principal climate effect of harvest. This immediate reduction in the carbon stock creates a deficit commonly known as the *carbon debt* (Fargione et al. 2008; Lamers and Junginger 2013). The deadwood and soil pools add a further, slower complication. They recover more gradually than the regrowing trees, so the forest's total carbon returns to its pre-harvest level later than tree regrowth alone would suggest.

How to quantify the climate consequences of this harvest is a subject of intense scientific debate. The controversy generally hinges on two critical methodological choices. The first is the spatial scale of the assessment, meaning stand versus landscape. A *stand* is a single, contiguous patch of trees of similar age and composition managed as a cohesive unit, whereas a *landscape* encompasses the wider forest estate made up of many such stands. The second choice is the reference system, and whether there should be one in the first place.

At the *stand level*, a harvest appears as a massive, immediate carbon emission followed by decades of slow regrowth. Its merit is that it causally isolates the effect of harvest where it happens. Proponents of the *landscape perspective* counter that forests are managed and decisions are taken not stand by stand but across whole estates. A managed landscape is a mosaic of stands of different ages;

while one stand is cut, others are actively growing. When aggregated across the whole forest, the dramatic fluctuations of individual stands even out, and the total carbon stock usually fluctuates around a stable or gently shifting trend line (Cowie et al. 2021).

This landscape stability is frequently invoked in policy and industry discussions to claim that bioenergy is carbon neutral (Cowie et al. 2021; Searchinger et al. 2018a). If annual harvest across an estate does not exceed annual growth, the total stock remains stable, leading some to argue that new harvests impose no additional climate impact. Critics argue this reasoning is flawed because it relies on misattribution over time and across stands (Searchinger et al. 2018a). It credits the ambient regrowth of older stands to offset the emissions of a newly cut stand. That older growth is recovering from past harvests and would have occurred regardless of the new cut. Widening the spatial boundary does not physically cancel the new emission. Furthermore, this perspective does not change that at any moment an unharvested forest holds more carbon than an otherwise identical harvested one (Nunery and Keeton 2010; Erb et al. 2018). Holtsmark (2012) finds that the debt remains even under aggregation, modelling a sustained 30% increase in harvest across the whole Norwegian forest, resolved into 75,000 parcels with an empirical age-class distribution.

This highlights the second, more fundamental methodological choice regarding the reference system, which is whether to measure against a counterfactual at all. National greenhouse gas inventories (Eggleston et al. 2006) and EU land-sector accounting (Section 2.3.2) do not. They report the observed net change in the forest carbon stock, a convention known in land use, land-use change and forestry (LULUCF) terminology as *gross–net accounting*. It has several practical advantages. It relies on measurable, auditable data, it ensures that reported stock changes align with what the atmosphere actually sees, and it requires no hypothetical baseline, which removes the scope for choosing one that favours a particular activity.

However, accounting on observed stock changes does not isolate the climate effect caused by the harvest itself. The measured flux folds in ambient regrowth, age structure shifts, and environmental drivers like CO_2 fertilization and does not account for the growth that might have occurred without harvest. Attributing a climate effect to a specific intervention requires a *counterfactual*, which is a statement of how the landscape's carbon stock would have developed had the harvest not taken place. When a harvested forest is measured against a no-harvest counterfactual, the managed stand sits below the baseline carbon stock for a prolonged period. The time taken to erase this carbon deficit relative to the counterfactual is the *carbon-parity time* – distinct from the absolute *payback time*, which only measures recovery to pre-harvest stocks (Figure 2.1).

Published estimates of these times differ widely, and much of the spread is real rather than a disagreement about forest growth. Parity time is set first of all by how fast the stand regrows, and therefore by biome, species, site productivity, and management (Lamers and Junginger 2013). Roundwood parity times run up to 400 years in boreal forests against a maximum of 50 years in the productive temperate forests of the south-eastern United States (Lamers and Junginger 2013). The remainder of the spread reflects what is being asked. A single felling repays faster than a permanently higher harvest level, and some estimates count the fossil emissions the wood displaces while others follow the forest alone. A dynamic analysis of wood replacing coal in eastern US forests puts the break-even at 44–104 years after clearcut (Sterman et al. 2018), whereas for a sustained 30% increase in harvest across the boreal Norwegian forest Holtsmark (2012) reports 190–340 years.

This framework distinguishes between *lost* and *forgone* carbon storage. *Lost* storage is a permanent, one-off reduction caused by a discrete land-use change, such as clearing a forest for cropland (Fargione et al. 2008). *Forgone* storage is the dynamic gap between the carbon stock the managed forest holds and the larger stock the unharvested counterfactual forest would have carried. It is therefore not an emission in the strict sense but a dynamic gap in carbon storage between the world in which harvest happens and the assumed counterfactual world in which it does not. Under a sustained harvesting regime, this recovery may never happen (Fehrenbach et al. 2022; Searchinger et al. 2018b).

Because forgone storage is defined against a reference baseline, the choice of baseline is a primary modelling decision (Soimakallio et al. 2015). Scientific debate therefore often focuses on which counterfactual is realistic. Proponents of the landscape perspective need not necessarily reject counterfactuals as such. They argue instead that a perpetual "no-harvest" baseline is the wrong one. Assuming a forest would remain unharvested ignores the risk of carbon losses to fire, drought, or pests, and overlooks the fossil emissions that would occur if society used coal or gas instead of the harvested wood. A third objection is that it disregards market dynamics (Cowie et al. 2021).

The argument from market dynamics rests on the fact that wood is a produced commodity, so higher demand for bioenergy raises timber prices. Price responses can in principle enlarge the forest carbon stock by rewarding afforestation on marginal land, drawing investment into faster-growing stands, and lengthening rotations (Sohngen and Mendelsohn 2003). Using the Global Timber Model,

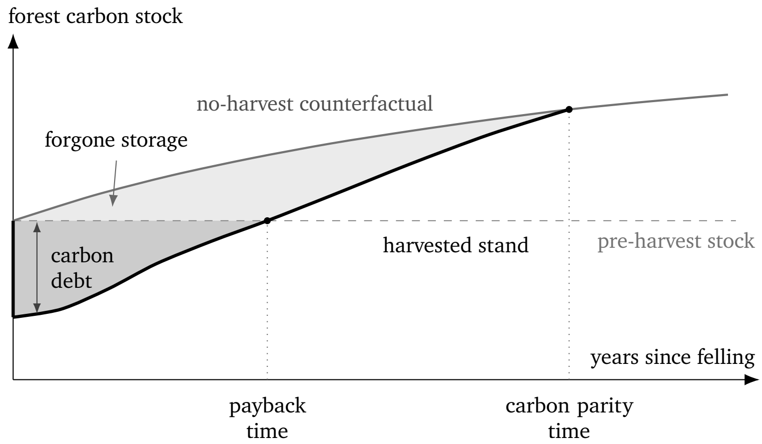


Figure 2.1: Carbon debt, payback time and carbon parity time, shown schematically for a single stand. Felling removes much of the standing biomass, and the resulting deficit relative to the pre-harvest stock is the *carbon debt*. The stock then recovers as the stand regrows, and the debt – the darker area – is repaid when it returns to its pre-harvest level, at the *payback time*. The unharvested counterfactual has gone on accumulating throughout, so the two trajectories meet only later, at the *carbon parity time*. The shaded area between them is the forgone storage, the quantity that the carbon-neutrality convention leaves out. Under a repeated rotation the next felling can arrive before parity, in which case the gap never closes.

Favero et al. (2020) find that a sustained rise in bioenergy demand can increase forest carbon stocks, as induced afforestation outweighs the additional harvest, and the same modelling literature puts sizeable areas of new forest within reach at moderate carbon prices (Austin et al. 2020). On this reasoning, the fixed-area, no-harvest counterfactual overstates the carbon debt by holding constant a forest area and management intensity that market demand would expand.

How much weight this carries depends on the price elasticity of forest area and management, which remains highly contested. Searchinger et al. (2025) argue that the land-supply elasticities driving strong afforestation results are exaggerated by a large factor, and empirical econometric estimates imply much more modest carbon-supply functions (Lubowski et al. 2006). Furthermore, they argue, the induced-investment effect would be slow and uncertain relative to the immediate, near-certain loss of stock at harvest.

This fundamental divide over counterfactual baselines and market responses is formalized in life cycle assessment (LCA) methodologies. The latest recommendations (Cowie et al. 2025; Koponen et al. 2018; Soimakallio et al. 2025) differentiate between two different types and conclude that their suitability depends on the question asked. The attributional approach (ALCA) addresses a descriptive accounting question, seeking to quantify the static share of global environmental burdens attributable to a specific product system. To isolate the absolute footprint of human management within this system, ALCA measures the active land use against a baseline of zero anthropogenic intervention, establishing *natural regeneration* as the appropriate reference level. Conversely, consequential LCA (CLCA) addresses a prospective cause-and-effect question, aiming to estimate the net change in global environmental flows resulting from a specific decision or policy intervention. Because CLCA seeks to model dynamic, market-mediated responses rather than a hypothetical absence of human activity, it evaluates impacts against an economic counterfactual, designating the *expected alternative land use* as the valid reference.

Ultimately, this lost and forgone logic governs every source of biomass. What changes between feedstocks is only the counterfactual. Dedicated energy crops occupy land that could otherwise store more carbon. This carries a forgone-storage cost with an additional lost-storage term if high-carbon land is converted (Fargione et al. 2008). Residues and wastes, such as straw, logging slash, and manure, are governed by the fate they would otherwise have met. The carbon cost is slight where the material would soon have decomposed anyway, but real where residues would have replenished long-term soil carbon. Residue status is, moreover, an economic category rather than a physical one, since what makes a flow a residue is that it carries no value of its own, and sustained demand for it can dissolve that condition (Section 5.2.2). Treating any feedstock as inherently carbon-free ignores this counterfactual of what the land or material would otherwise have done.

2.1.2 Product fate and substitution

The harvest debt is only half of the balance. What fixes the net climate effect is also what becomes of the carbon once it leaves the forest, and how that compares with what would have been emitted in wood's absence.

The first half of this is timing. Harvested carbon returns to the atmosphere at a rate set by how the wood is used, within the year of combustion for energy wood, within a few years for short-lived products such as paper and packaging, but over decades for sawnwood and engineered timber in buildings. The shorter the service life relative to the regrowth it must be set against, the larger the residual debt – so much so that the climate impact of a given quantity of wood depends heavily on its end use (Helin et al. 2016).

The second half is substitution. Wood can displace more emission-intensive materials, such as concrete and steel, and fossil fuels. The conventional approach credits the emissions thereby avoided directly against the wood product's carbon cost, through a *displacement factor* (DF), the tonnes of fossil carbon avoided per tonne of carbon in wood used (Sathre and O'Connor 2010; Myllyviita et al. 2021).

Crediting in this way runs together two distinct questions: what the climate cost of producing and using a wood product *is* and whether that product is *preferable* to the alternative it might replace. The first is a property of the product. The second is a comparison between options, and its answer turns on an assumed counterfactual material or fuel that has nothing to do with the forest. This is the same attributional and consequential divide as in Section 2.1.1, arising a second time at the product boundary rather than at the forest baseline.

The displacement factors used for that comparison are themselves contested. The widely cited average of about 2.1 $tC\,tC^{-1}$ (Sathre and O'Connor 2010) has been challenged on four grounds: the fossil reference systems it assumes predate current material production, forgone carbon storage is not included, the mass-substitution ratios exceed those observed in paired building studies, and a large share of published estimates trace back to a small number of primary sources (Leturcq 2020; Myllyviita et al. 2021).

2.1.3 Forest-carbon and life-cycle models

Two research traditions dominate the quantification of the carbon profile of wood, and they have largely developed in parallel. The first uses forest growth and carbon models, from inventory-based national budget models such as CBM-CFS3 (Kurz et al. 2009) to the harmonized European biomass and increment datasets that now feed them (Avitabile et al. 2024), and it is this work that established the carbon debt described above (Holtsmark 2012; Mitchell et al. 2012). A closely related strand of inventory accounting follows the net flux at national and continental scale, and reports the European forest sink as finite and now declining. The sink absorbed about 436 Mt CO_2-eq per year over 1990–2022, roughly a tenth of the EU's anthropogenic emissions, but fell from about 457 to 332 Mt CO_2-eq per year between 2010–2014 and 2020–2022, driven by higher harvest rates, increased natural disturbances, and slower growth under a changing climate (Migliavacca et al. 2025).

The second tradition, life-cycle assessment (LCA), tracks carbon through processing, use, and end-of-life, and is the established instrument for product-level climate accounting under the ISO 14040 and 14067 standards (International Organization for Standardization 2006; International Organization for Standardization 2018).

Applied to wood, four recurring limitations of current LCA practice have been observed.

The first is the omission of forgone carbon storage. Where the dominant convention treats biogenic CO_2 as climate-neutral, changes in the forest carbon stock never enter the product balance (Cherubini et al. 2011; Røyne et al. 2016). Wood then arrives at the boiler with an emission factor of zero, so co-firing it in a coal plant scores the full avoided emissions of the coal displaced. Yet wood is converted to electricity less efficiently than coal and loses more in processing, so the immediate effect of the substitution is to raise atmospheric CO_2 rather than lower it (Sterman et al. 2018). Once the stock changes are counted, the apparent benefit of wood use shrinks and, for short-lived products, can reverse outright (Soimakallio et al. 2016; Searchinger et al. 2018b).

The second is fragmented system boundaries. The minority of studies that do include forest carbon typically solve the forest dynamics and the product-substitution system as separate models and add their results together at the end, rather than closing them against the standing forest in a single mass balance. This prevents consistent attribution of the forest-carbon cost to individual products and their co-product chains (Fehrenbach et al. 2022; Soimakallio et al. 2016). One such correction assigns a forest carbon-storage balance of 0.25 to 1.15 t CO_2-eq per cubic metre of wood, enough to turn energy wood from a saving into a net source (Fehrenbach et al. 2022).

The third is narrow scope. Most integrated assessments cover a single country or a few case studies (Soimakallio et al. 2016; Helin et al. 2016), or resolve only a handful of lumped product classes where the scope is global (Peng et al. 2023). Neither transfers cleanly to the European scale, where growth rates, species mixes, and product portfolios differ markedly between the northern, central, and southern regions, so a figure that is right for Finland need not hold for central-European or Mediterranean stands.

The fourth concerns the treatment of time. Where the timing of carbon flows is addressed at all, it is handled either with physical metrics that require a time horizon fixed by convention or with discount rates taken from financial appraisal, whose relation to the changing damage a tonne of CO_2 does over time is not defined (Brandão et al. 2013; Cherubini et al. 2011; Peng et al. 2023). This problem is not peculiar to wood, and it is addressed in Section 2.2.

2.1.4 No single framework joins forest carbon, products, and time

No single study has yet coupled mass-balanced life cycle dynamics, per-product resolution across the diversity of European feedstocks, and a welfare-consistent way of weighting flows over time. Paper II addresses this with a newly developed model, ClimFor, which tracks carbon in a closed mass balance from forest growth through harvest, processing, and use to end-of-life, resolves it per product across European conditions, and expresses each product as a single emission factor, with substitution computed outside the mass balance and reported as a separable layer, so that the attributional carbon accounting and the consequential displacement credit can be read on their own as well as combined. To collapse the time series of CSCs into single emission factors, Paper II relies on the framework of Paper III.

2.2 Valuing emissions over time

The metrics that dominate climate accounting were built in the 1990s for questions that did not include weighting emissions over time. National greenhouse-gas inventories (IPCC 1997; Eggleston et al. 2006), the equivalence metrics introduced in the First Assessment Report (Houghton et al. 1990), and the life-cycle conventions that took both as inputs (International Organization for Standardization 2006; International Organization for Standardization 2018) were designed to tally annual emissions and to compare different gases emitted within a single year, not to weigh a tonne emitted now against a tonne sequestered a decade later. Yet that is exactly the decision biomass demands, since its harvest sets in motion a trajectory of CSCs that unfolds over decades (Section 2.1). Whenever options with different emission timing are compared, a judgement has to be made about how to weight those flows over time.

2.2.1 Why weight emissions?

The reason we weight goods or ills over time – money, consumption, or consumption-equivalent damages – is that their value or their harm changes depending on when we gain or endure them. One reason we might value the same consumption less in the future, for instance, is that we expect to be richer then, and with increasing wealth, the marginal welfare benefit – the well-being we gain – from that consumption diminishes.

The damage done by an emission of CO_2, too, depends on when it occurs.

A tonne of CO_2 does harm not only at the moment of its release but over long time horizons. Once emitted, much of it stays in the air for centuries (Joos et al. 2013), warming the planet and causing damage year after year. This is why timing matters even before any value judgement is made – an early tonne and a late tonne lay their effects over different stretches of the future, with the early emission causing interim damages before the later emission happens.

Equivalently, emitting now rather than later can be compared to emitting later plus releasing a temporary tonne in the meantime, much like a short-lived gas such as methane. The cost of emitting early and the benefit of delaying or storing carbon are the same quantity – the interim damage – so any metric that prices one must price the other. Delaying a CO_2 emission is therefore always a benefit. (The damage integrals of two pulses do not overlap exactly, but for a long-lived gas such as CO_2 the statement holds across realistic assumptions.)

How large that benefit is depends on how the avoidable interim harm compares with the harm that occurs either way, which in turn requires assessing how the same unit of warming causes damage in different years. Damage rises faster than linearly with temperature, so an extra degree hurts more in an already-warm world than in a cool one (Howard and Sterner 2025), and a larger, richer economy has more people and assets exposed to every degree. Better adaptation works the other way, but on standard assumptions a given amount of warming does more harm the later it occurs. This does not make delay any less valuable in itself, as the early tonne still inflicts the interim harm on top of everything the late tonne does.

The value of delay is raised, in turn, by how future damage is weighed against present damage. Future losses are usually counted for less, for two reasons. Future generations are expected to be richer, so a given loss costs them less well-being. In addition, many people apply some *pure time preference*, valuing later welfare a little less simply for being later, an ethical judgement on which views differ sharply (Drupp et al. 2018). Because this lightens the far-future harm that delay cannot remove, it leaves the avoided interim harm weighing more heavily, and so makes delaying more valuable.

The extent to which later emissions are down-weighted is therefore set by two effects, a more vulnerable future lowering the relative value of delay and discounting raising it. Not down-weighting future CO_2 emissions at all, however, would mean that interim damages are ignored completely.

2.2.2 Collapsing time with a fixed horizon

The equivalence metrics were built to map a one-off pulse of a gas to its path of climate effect and reduce that path to a single number, so that a tonne of methane can be stated in tonnes of CO_2. Aggregating one gas across many years, as a CSC profile demands, is a different question, and the standard response is to carry the pulse logic over and simply stop the clock at a chosen point, neglecting everything that happens beyond it.

The hundred-year Global Warming Potential (GWP_{100}) that underpins national inventories and most life-cycle assessment integrates a pulse's radiative forcing over one century, relative to CO_2. The Global Temperature change Potential (GTP) instead reads the temperature anomaly at a single endpoint rather than integrating along the way (Shine et al. 2007), discarding everything before that year. The two differ only in what they fix, a horizon to integrate to or an endpoint to read, yet both reduce a one-off pulse to a single number by disregarding all that lies beyond that point. The strong dependence of these metrics on the chosen horizon is well documented (Fuglestvedt et al. 2003).

A few approaches were built specifically for emissions spread across time. Dynamic LCA keeps every emission dated. Where conventional life-cycle assessment treats each one as though released in the same instant, dynamic LCA convolves the dated emission series with time-dependent characterization factors. The result is a full trajectory of radiative forcing or temperature rather than a single static score (Levasseur et al. 2010; Wiloso et al. 2026). GWP_{bio} applies the same time-explicit logic to a single biogenic system, scoring the combustion pulse and the slower regrowth removal against a fixed horizon so that the warming caused while the carbon remains in the atmosphere is counted rather than assumed away (Cherubini et al. 2011). Both date their fluxes explicitly, which is what the delayed, drawn-out profile of a harvested forest requires.

Even these methods, however, do not leave the tradition behind. Their indicator stays physical – radiative forcing or temperature, with no account of how the resulting damage is valued – and, to compress a trajectory into a number a decision can act on, the analyst must still integrate it to a chosen horizon. What changes is the shape of the implicit weight, not the fact that the horizon fixing it is set by convention. A fixed, undiscounted window counts every tonne inside it in full and nothing beyond, a step that drops to zero at the horizon, whereas dynamic LCA and GWP_{bio} integrate each emission's forcing only over its remaining window, so the weight ramps down to zero instead (Figure 2.2).

The same fixed-window logic is embedded in regulation. The EU Renewable

Figure 2.2: Implicit time weighting under a fixed horizon. Each curve shows the weight placed on a CO_2 emission as a function of when it occurs, relative to an emission in the decision year. A fixed, undiscounted accounting window – shown at the twenty-year horizon of the land-use amortization of the EU Renewable Energy Directive (RED) (European Parliament and Council of the European Union 2018) and the thirty-year horizon of the U.S. Renewable Fuel Standard (RFS) (U.S. Environmental Protection Agency 2010) – counts a tonne in full if it falls inside the window and not at all beyond it, a step that drops to zero at the cutoff. Dynamic LCA and GWP_{bio}, shown at horizons of 50 and 100 years, instead integrate each emission's forcing only over its remaining window to the horizon, so the weight declines smoothly to zero. Both place the cutoff by assumption. The curves are derived from the CO_2 impulse-response function of Joos et al. (2013), with radiative forcing taken proportional to the airborne fraction and no discounting applied.

Energy Directive (RED) annualizes life-cycle emissions over a fixed twenty-year amortization period (European Parliament and Council of the European Union 2018), and the U.S. Renewable Fuel Standard evaluates them over thirty years (U.S. Environmental Protection Agency 2010). Offset frameworks impose durability rules of their own, such as the hundred-year permanence threshold of compliance protocols (California Air Resources Board 2014).

Part of the appeal of the fixed window is that it appears to avoid the discount-rate question. By weighting every tonne inside the horizon equally and discounting none of them, it presents itself as a physical convention, a matter of atmospheric science rather than ethics. It is not, however, free of a time-weighting choice. Declining to discount within a window is itself a weighting schedule, uniform inside the horizon and zero beyond it, and the position of that horizon changes the result. Moving between twenty, one hundred and five hundred years reorders the ranking of mitigation options (Levasseur et al. 2010; Brandão et al. 2013). Endpoint metrics such as GTP discard the interim altogether and score a pathway that overshoots sharply and one that approaches the same endpoint smoothly as equivalent.

2.2.3 Discounting and the social cost of carbon

The alternative to a cutoff is a rate that lets the weight fall off smoothly. Its simplest form applies an ordinary financial discount rate straight to physical tonnes. Searchinger et al. (2018b) and Peng et al. (2023), for instance, use 4% per year over a hundred-year horizon, reasoning by analogy to real returns on investment and to policy time frames. Applying continuous discounting avoids the cliff edge of the window (even though in the above example, a window is used as well), but a financial rate applied to physical mass has no defined relation to climate damage. It down-weights a future tonne without reference to the harm that tonne will do, so it does not represent the dependence of marginal damages on the climate state and on the size and vulnerability of the economy the tonne acts upon, nor their non-linear change as the world warms.

The discipline that does tie weight to harm is the economics of the social cost of carbon (SCC). The SCC is the present-value welfare damage of emitting one additional tonne of CO_2 in a given year, obtained by propagating the emission through a climate model and a damage function and discounting the resulting stream of future losses back to the present (Rennert et al. 2022b). Built into it is what the physical metrics omit, namely an explicit account of how damage grows as temperature and exposed wealth rise, and an explicit, if contested, statement of how future welfare is valued against present. This welfare reasoning has lately been extended to time-structured problems. The social value of offsets prices temporary and reversible storage by the present-value damage it averts (Groom and Venmans 2023; Groom and Venmans 2025), giving a continuous alternative to the binary permanence thresholds of offset markets, derived from damages rather than set by convention.

For the purposes of this thesis, however, the economic route stops just short of what is needed. The SCC and the social value of offsets are expressed in money, whereas the object that must be reported, regulated, and optimized is often an amount of CO_2.

The idea of grounding gas comparisons in welfare rather than physics is not new. Economists proposed damage- and welfare-based alternatives to GWP as early as the 1990s, weighting each gas by the present-value harm it does instead of by its radiative forcing (Kandlikar 1996; Hammitt et al. 1996). These indices, however, were again built to compare different gases emitted in a single year, not to aggregate one gas across many. Neither, then, delivers a transparent weight that can be laid over any CSC profile and summed to a single equivalent quantity.

A prior attempt to weight CO_2 emissions by the social cost of carbon discounted each pulse's damages back only to its specific year of emission, rather than to a common decision year (Sproul et al. 2019). Because the discounting base year moves with the pulse, the damages accruing between an earlier emission and a later one fall outside both valuations, and the comparison returns later emissions as invariably worse than earlier ones. Rebasing every pulse to a common decision year retains those interim damages, which is the approach taken in Paper III.

2.2.4 No welfare basis for weighting emissions over time

What previous metrics do not provide – and what Papers I and II need to express carbon dynamics as emission factors – is a weighting schedule that is welfare-consistent like the SCC yet applicable to and expressible as tonnes like a physical metric, and that does not rely on a time horizon fixed by convention.

This is the gap Paper III addresses. It derives a schedule of time weights for CO_2 from the same social-cost-of-carbon impact chain, by comparing the present-value welfare damage of marginal pulses emitted in different years, all valued at a common decision year.

2.3 Bioenergy in the EU energy system

Section 2.1 set out the carbon cost of harvest and Section 2.2 how to weight it over time. This section turns to where that cost is incurred in practice: how biomass is currently used and regulated in the EU, and how it is represented in the energy-system models that inform policy.

2.3.1 Scale and role of biomass

Bioenergy is the largest single source of renewable energy in the European Union. In 2024, renewable sources met just over a quarter (25%) of the EU's gross final energy consumption, of which biomass – solid, liquid, and gaseous combined – supplied roughly half, ahead of wind, solar, and hydropower (Eurostat 2025b). About 70% of this bioenergy is solid biomass, the remainder being liquid biofuels (around 13%), biogas (around 10%), and the renewable fraction of municipal waste. It is mainly from woody biomass – forest stemwood, logging residues, and wood-processing by-products such as sawdust, bark, and black liquor – but also draws on agricultural residues such as straw, crop-based liquid biofuels, and biogas feedstocks such as manure and energy crops (European Commission et al. 2024). Its use is concentrated in heat, where biomass is by far the largest renewable source. In electricity, it plays a smaller role, supplying a little over a tenth of the EU's renewable power. In transport, it appears mainly as liquid biofuels (Eurostat 2025b).

Biomass demand is expected to grow. The International Energy Agency (IEA) expects global modern bioenergy use to more than double by 2050, from around 40 to roughly 100 EJ in its Net Zero scenario (International Energy Agency 2024). In the EU, biomass and waste currently supply about 1,700 TWh (6.1 EJ) of primary energy, comparable to the entire annual energy consumption of Italy (Eurostat 2025a). The Commission's net-zero pathways project this level to grow by up to around 80% by 2050 (European Commission 2018a). Reasons for this expected growth in demand are the unique properties of biomass.

Unlike weather-dependent wind and solar, biomass is dispatchable and storable, and as a carrier of biogenic carbon it is one of the few routes to drop-in fuels for aviation and shipping and, coupled with carbon capture and storage (CCS), to negative emissions (Millinger et al. 2025; Mandova et al. 2019; Tanzer et al. 2020). That systemic value, when biomass is treated as carbon neutral, is large. On one measure of it, the cost of doing without, Millinger et al. (2025) find that removing bioenergy from a net-zero European energy system would raise total system costs by roughly 14%, making it about as valuable as wind power.

2.3.2 The carbon-neutrality assumption in EU policy

The conventional case for bioenergy's climate benefit rests on the circularity of biogenic carbon – the premise, examined in Section 2.1, that combustion merely returns carbon the plant recently took up. As shown there, this neutrality holds only under restrictive, steady-state conditions. Once the timing of recapture and the carbon storage a standing forest would otherwise have provided are accounted for, the carbon balance becomes valuation and time-dependent (Searchinger et al. 2018b; Fehrenbach et al. 2022).

This carbon-neutrality assumption was formalized, in a deliberately limited form, by the Intergovernmental Panel on Climate Change (IPCC) guidelines for national greenhouse-gas inventories. To avoid counting the same emission twice, the 2006 IPCC Guidelines record CO_2 from biomass combustion only as an information ("memo") item in the energy sector, excluded from the sectoral and national totals, and account for the carbon instead as a stock change in the land sector (LULUCF) at the moment of harvest (Eggleston et al. 2006). The land-carbon effects are therefore acknowledged – they are simply booked elsewhere. The IPCC is explicit, however, that this is an accounting choice about *where* an emission is recorded, not a finding that bioenergy is climate neutral.

European climate policy adopted this accounting convention. The IPCC rule relocates where an emission is recorded, leaving biomass combustion out of the energy sector so that the carbon can be counted in the land sector instead. In EU policy, biomass is classified as renewable and its combustion emissions are zero-rated. Against the IPCC's own framing of the rule as a recording choice rather than a finding of climate neutrality, a sustained scientific critique argues that EU policy treats the energy-sector zero as evidence of neutrality and applies it without ensuring the recapture of carbon on which the convention depends (Norton et al. 2019; Searchinger et al. 2018b).

This effectively carbon-neutral treatment is embedded in three concrete instruments. The *Renewable Energy Directive* (RED) decides what counts as renewable and on what terms, the *Emissions Trading System* (ETS) decides what it costs, and the *LULUCF Regulation* is where the land carbon is meant to reappear in the accounts.

The RED treats bioenergy as renewable and sets the sustainability and greenhouse-gas-saving criteria a fuel must meet (European Parliament and

Council of the European Union 2018; European Parliament and Council of the European Union 2023a). The saving is measured along the supply chain – cultivation, processing, transport – and combustion CO_2 is booked as zero emissions. There is a term for the carbon released by direct land-use change, say when forest is cleared for cropland, but none for the carbon a forest would have gone on storing had it not been cut for fuel. The directive therefore accounts for carbon lost to conversion but not for carbon forgone to ordinary harvest.

In the ETS, biomass that meets the RED criteria is "zero-rated", so its combustion carries no cost in the market that otherwise governs emissions from power and industry (European Commission 2018b; European Parliament and Council of the European Union 2023b).

The LULUCF Regulation is supposed to be where this carbon is finally booked, against an EU target of 310 Mt CO_2-equivalent of net removals by 2030 (European Parliament and Council of the European Union 2023c). Until 2025 a country's managed forest was assessed against a projected *forest reference level*, a modelled baseline for how the sink would develop if the management practices of 2000–2009 continued, including the effect of shifting age classes (Vizzarri et al. 2021). This construction projects a continuation of past management rather than a no-harvest state, so harvest at the projected level produces no debit. Setting these levels proved contentious and depended heavily on modelling choices (Vizzarri et al. 2021), and the baseline in any case does not isolate the carbon forgone by additional felling. From 2026, the reference level is removed, and compliance rests instead on the net flux reported for the land sector as a whole, measured against a fixed target (European Parliament and Council of the European Union 2023c). An extra tonne harvested is therefore not separately identifiable in the reported totals.

Together, these instruments produce what Booth and Giuntoli (2025) term a structural decoupling: in the accounts, biomass use in the energy sector is separated from its consequences on the land. The land-sector record captures part of that carbon, but not all of it. Imported biomass is charged not to the EU but to the exporting country's inventory, which need not be bound by it (Searchinger et al. 2009; Norton et al. 2019). Domestic harvest does enter the accounts, but only as a reduction in the land sector's net flux, counted against an absolute removals target. It is not compared with the carbon an unharvested forest would have kept storing, so the growth forgone by cutting for energy is not separately reported (European Parliament and Council of the European Union 2023c; Booth and Giuntoli 2025).

The EU forest sink on which the carbon-neutral logic rests has moreover been declining for over a decade, and the 2030 removal target is reported as off track (Booth and Giuntoli 2025; Searchinger et al. 2022). Recording a tonne in the land-sector accounts also does not price it where biomass is chosen. The carbon market, the directive, and the models built on them apply the neutrality convention, so the carbon cost is not internalized at the point of use.

2.3.3 Biomass in energy-system models

What decarbonization studies find biomass to be worth depends on what their models contain. Of 180 studies of fully renewable energy systems published between 2004 and 2018, many contain only the electricity sector (Hansen et al. 2019). Within that boundary, no other sector competes for the feedstock. Zappa et al. (2019) find that a fully renewable European power system in 2050 would require at least 8.5 EJ of biomass for electricity alone, against the roughly 6 EJ of biomass and waste that supplies all sectors of the EU energy system today (Eurostat 2025a). Reviewing 24 such scenarios, Heard et al. (2017) objected to the sheer area of land they commit to energy cropping, and to its competition with food production and conservation. Brown et al. (2018a) replied that more recent studies assess the potential explicitly or restrict biomass to agricultural residues and waste, and that some exclude it altogether and still reach feasible and cost-effective systems

In recent models that resolve the sectors competing for the feedstock, biomass is valued for its biogenic carbon. As mentioned above, it provides a renewable source of carbon for fuels that resist electrification, such as aviation and shipping, and, combined with capture, a route to negative emissions. Electricity is then a minor use, with biomass supplying about 1% of generation in a cost-optimal net-zero European system (Millinger et al. 2025). A second sector-coupled model likewise finds biomass more valuable for decarbonizing transport than for balancing variable renewable supply or heating buildings (Wu et al. 2023). Across the European system, this value is found to be large and spread over many usage pathways rather than concentrated in one technology (Millinger et al. 2025; Millinger et al. 2022), and near-optimal analyses find biomass in most fossil-free system configurations (Pickering et al. 2022).

Energy-system optimization models also inform European energy and climate policy, since the Commission's assessments are built on them (European Commission et al. 2021) and models and policy influence one another (Süsser et al. 2021). How large the value of biomass appears, therefore, depends on how the models represent it.

Almost without exception, energy-system models such as PyPSA-Eur (Hörsch et al. 2018) and Calliope (Pfenninger and Pickering 2018) inherit the carbon-neutrality convention. Biomass enters with zero combustion emissions and no carbon cost. Its deployment is usually limited by an exogenous cap on supply, which also excludes the feedstocks that the underlying potential assessments classify as unsustainable, and up to that cap the feedstock is available at a fixed extraction cost (Millinger et al. 2022; Pickering et al. 2022). That cap is usually taken from biomass-potential assessments such as the ENSPRESO database (Ruiz et al. 2019), which bound how much biomass is available but not the carbon consequence of using it.

Which assessment a model adopts, and which of its scenarios, therefore matters. ENSPRESO alone offers low, medium, and high availability scenarios (Ruiz et al. 2019), and the wider potential literature diverges further still. A review of seventeen global studies found projections for 2050 ranging from below 100 to above 400 EJ yr^{-1} (Berndes et al. 2003), whereas a later multi-author assessment reported high agreement on a sustainable technical potential of up to 100 EJ, medium agreement between 100 and 300 EJ, and low agreement above that (Creutzig et al. 2015). Slade et al. (2014) attribute the spread to the assumptions the estimates rest on rather than to the data behind them. Models also tend to use the whole amount allowed. Zeyen et al. (2021), for instance, exhaust the entire assumed biogas potential in every scenario they run.

A few studies refine the inventory at the margins. Lauer et al. (2023) add supply-chain process emissions, and Millinger et al. (2025) a small emission factor on imported biomass alone. Two go further. Czyrnek-Delêtre et al. (2016) attach direct and indirect land-use-change factors to each bioenergy commodity in an Irish TIMES model, though the direct factors are computed as the difference between two static carbon stocks and so register the storage lost at conversion rather than the sequestration the land would have continued to provide, and forest feedstocks carry none. Kouchaki-Penchah et al. (2023) couple a forest carbon-budget model to a TIMES model of Quebec so that the biogenic carbon of forest bioenergy enters the optimization and changes which technologies are built. Crops and short-rotation woody biomass, however, remain carbon neutral. Both are single-country studies resolved in twelve and sixteen intra-annual time slices.

Integrated assessment models (IAMs) couple energy and land use in one framework and so endogenize the trade-off that energy-system models leave out, namely the carbon released when land is cleared or diverted to grow the feedstock (Mandley et al. 2022; Zhao et al. 2024). Bioenergy is valuable across a wide range of these models (Rose et al. 2014), and frameworks such as GCAM, IMAGE, MESSAGE–GLOBIOM, and REMIND–MAgPIE resolve its supply against competing demands for food, land, and terrestrial carbon through explicit land-use modules (Popp et al. 2017).

In these models, the land-use emissions of biomass are not a fixed property of the fuel. They rise or fall with the policy scenario, above all with whether the carbon stored in land is priced alongside fossil carbon. Wise et al. (2009) demonstrated the effect, finding that a carbon price on fossil emissions alone, with land carbon left unpriced, drives bioenergy expansion into forests and other high-carbon land. That dependence is large. In REMIND–MAgPIE, Merfort et al. (2023) derive an effective biofuel emission factor that stays near 12 kg CO_2 GJ^{-1} where land and energy carbon are priced together but rises to 64–92 kg CO_2 GJ^{-1} without comprehensive land-use regulation, a difference that reflects the greater use of carbon-intensive feedstocks once the terrestrial carbon they displace carries no price. In the same vein, Harper et al. (2018) find that land-use-change losses can offset much of the carbon that biomass with capture is credited to remove.

What IAMs trade for their scope is temporal and spatial resolution. They represent the power sector in a few aggregated time slices and regions rather than at hourly detail, and model variable-renewable integration through parameterized approximations (Pietzcker et al. 2017; Collins et al. 2017). This aggregation is known to bias the valuation of the dispatchable and storage technologies whose worth depends on short-term balancing (Bistline 2021), biomass among them. The two model families are therefore complementary. IAMs account for the carbon released or forgone when land is turned over to biomass but resolve the power system in coarse time slices, whereas energy-system models resolve it at hourly detail while treating that same carbon as zero. Recent work soft-couples the two (Odenweller et al. 2026), yet the information they exchange concerns power-system flexibility, not the change in each feedstock's own land-carbon stock that is the subject of this thesis.

2.3.4 Land carbon missing from high-resolution energy-system models

The CSCs of producing biomass feedstocks are still missing from the models that resolve the energy system in the most detail. The refinements noted above reach only part of the way. Supply-chain process emissions and a factor on imported biomass alone are not CSCs (Lauer et al. 2023; Millinger et al. 2025), and the two models that do carry land carbon into the optimization cover a single country in twelve and sixteen intra-annual time slices and account for only part of the feedstock portfolio (Czyrnek-Delêtre et al. 2016; Kouchaki-Penchah et al. 2023). Because biomass is otherwise treated as carbon-neutral, omitting these CSCs lowers its modelled cost relative to the alternatives, so those models deploy more of it than they would were the emissions counted.

Chapter 3

Methodology

While the full details of the methods reside in the appended papers and their supplementary information, this section gives a high-level overview of the key frameworks and modelling decisions.

I will start by summarizing the method of Paper III, which derives a welfare-equivalent rate for time-weighting emissions. I follow with Paper II, explaining how ClimFor models CSCs in forests, and end with Paper I and the integration of the resulting emission factors into PyPSA-Eur. Figure 3.1 summarizes what each tool takes in and what it produces.

3.1 Welfare-equivalent CO_2 (Paper III)

3.1.1 Concept and definition

The central idea of the welfare-equivalent CO_2 framework is to compare CO_2 emissions at different points in time based on their net-present welfare impacts. In other words, comparing them based on how they impact the well-being of our global population.

This impact follows from a causal chain that starts with the emission, which then changes global temperatures, which causes damages to our global society and economy that can be expressed as consumption-equivalents, and ends with the time-weighting of those damages through social discounting. Each step in this causal chain hinges on conditions that are time-dependent. For instance, the temperature change incurred by an emission is influenced by the state of the climate. Similarly, the damage done for each marginal temperature change hinges on the vulnerability of society, which changes as more wealth is exposed to damage and as the climate warms. The last step in the chain, social discounting, also hinges on timing.

Social discounting is commonly expressed using the Ramsey rule (Ramsey 1928), which weights consumption based on a pure time preference ρ and a wealth term which represents the diminishing value of marginal consumption with increasing wealth. η describes the speed at which consumption becomes less valuable as people become richer (the elasticity of the marginal utility of

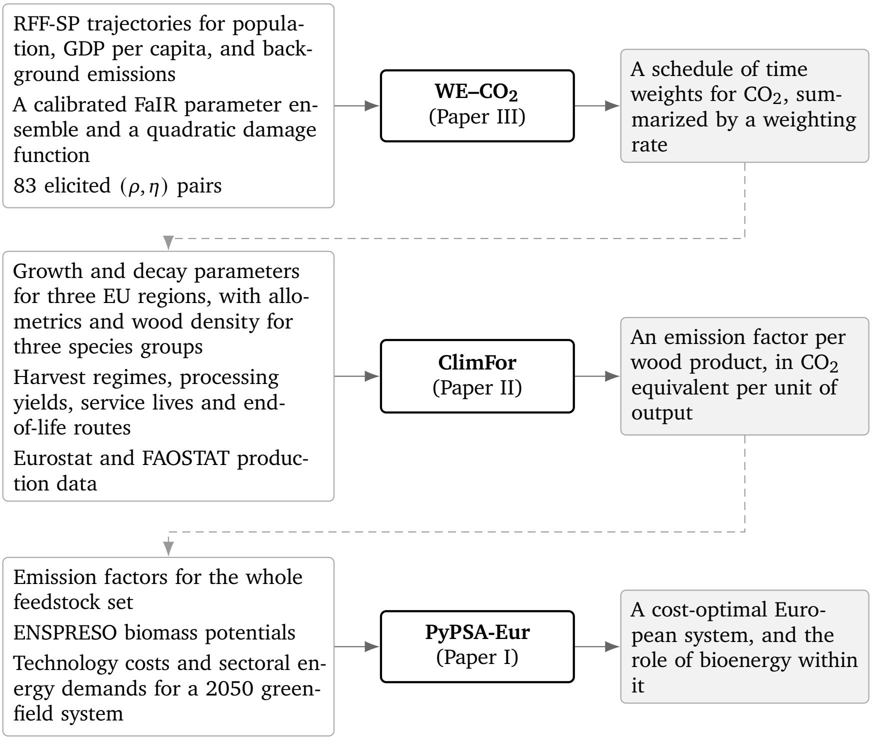


Figure 3.1: The three modelling tools, their inputs and their outputs. Each row reads from the data the tool consumes, through the tool itself, to the quantity it produces. The dashed connectors show where one tool's output becomes the next one's input.

consumption), and g_c is the growth rate of per-capita consumption, the growth in wealth. The rate at which consumption is down-weighted can then be expressed as:

$$r_s = \rho + \eta\, g_c\,, \tag{3.1}$$

This impact chain is the same as for the calculation of the social cost of carbon (SCC), which expresses, in monetary terms, how much welfare damage an emission does in a given year. Because the damage of an emission can be expressed using the SCC, we can use that metric to define the relative welfare costs of emissions in different years. However, because the SCC is expressed in net present value discounted to the year of the emission, comparing emissions across years means the SCC values need to be rebased to a common year, which I refer to as the decision or base year t_0.

The relative importance of an emission in year t is then:

$$w(t) = \frac{\mathrm{SCC}_{t_0}(t)}{\mathrm{SCC}_{t_0}(t_0)}\,, \tag{3.2}$$

and therefore normalized so that $w(t_0) = 1$.

The schedule of time-weights, or CO_2 weighting factors, can be described by a rate that describes their change. The CO_2 weighting rate at any given point in time is then:

$$r_{w,\mathrm{local}}(t) = -\frac{\mathrm{d}}{\mathrm{d}t} \ln w(t)\,. \tag{3.3}$$

As long as the SCC over an infinite horizon stays finite, the CO_2 weighting rate at a particular point in time equals the social discount rate minus the rate at which the conventionally valued SCC (discounted to the year of emission) increases over time. This entails that when marginal damages grow over time (due to increasing temperatures and a growing economy), the CO_2 weighting rate is lower than the social discount rate, meaning later emissions are not discounted as steeply as a naive application of the social discount rate would suggest.

Equation (3.3) is an instantaneous rate that varies with t. Every rate quoted as a single number in this thesis is instead r_w, the constant discrete-compounding rate fitted to the whole schedule (Section 3.1.3) and used in Equation (3.4) below; the two are related by $1 + r_w = e^{\bar{r}_{w,\mathrm{local}}}$, where $\bar{r}_{w,\mathrm{local}}$ is the effective continuous rate over the horizon.

When the CO_2 weighting schedule is applied to a time-series of CSCs, we can calculate the welfare-equivalent CO_2 – the amount of CO_2 emitted in the base year that would yield the same net present welfare damages as the entire stream of CSCs:

$$\text{WE–CO}_2(t_0) = \sum_t \text{CSC}(t) \cdot w(t) = \sum_t \text{CSC}(t) \cdot (1 + r_w)^{-(t-t_0)}. \qquad (3.4)$$

3.1.2 Modelling setup

To evaluate the time-dependent impacts of CO_2 emissions, we implement a sequential modelling framework that propagates marginal emissions through the impact chain described above.

The core approach relies on a pulse-response methodology. Each emission year is treated as a separate simulation, in which a marginal CO_2 pulse is added to the baseline emissions trajectory in that year and propagated to the end of the modelling horizon, which extends 600 years beyond the base year. Taking the difference between this perturbed run and the baseline isolates the marginal impact of the emissions released in that specific year.

The baseline trajectories for global population, gross domestic product (GDP) per capita, and background greenhouse gas emissions are drawn from the Resources for the Future Socioeconomic Projections (RFF-SP) (Rennert et al. 2022b). Using these baseline inputs, the modelling chain proceeds through three main modules:

- **Climate Module:** We use the reduced-complexity climate model FaIR v2.2.2 (Leach et al. 2021; Smith et al. 2024). FaIR maps the given emissions trajectories to atmospheric greenhouse gas concentrations, radiative forcing, and resulting global-mean surface temperature anomalies. To represent parametric climate uncertainty and ensure consistency with assessed historical warming, we use the calibrated FaIR parameter ensemble of Smith et al. (2024) and Smith (2025).
- **Damage Module:** The resulting temperature anomalies are translated into economic impacts using a quadratic damage function. This function maps temperature changes (relative to pre-industrial levels) directly to a fractional loss of global economic output.

- **Social Discounting and Welfare Aggregation:** To evaluate these future damages in present-value terms, the global economic losses are converted into consumption-equivalent welfare. We apply Ramsey-style social discounting with an isoelastic utility function, which uses the pure rate of time preference (ρ) and the elasticity of marginal utility (η) as defined above (Ramsey 1928). Baseline GDP-per-capita growth is used as a proxy for per-capita consumption growth to dynamically determine the discount factor over time.

3.1.3 Treatment of uncertainty

The framework separates two kinds of uncertainty that differ in kind. Which socioeconomic trajectory and climate response materialize is an empirical question about how the world will evolve. The Ramsey parameters (ρ, η) instead encode a normative position held by the evaluator, on which experts genuinely disagree. The two are therefore aggregated in separate layers rather than pooled into a single distribution.

We evaluate all 10,000 RFF-SP trajectories, each paired with one draw from the calibrated FaIR parameter ensemble, under each of the 83 unique (ρ, η) pairs elicited from 181 economists and philosophers by Nesje et al. (2023), giving 830,000 trajectory–preference combinations. Summary statistics weight each pair by its respondent count. Empirical uncertainty is integrated within each preference view, while the disagreement across views is reported as a separate layer, with interquartile and 5th–95th percentile ranges across views expressing its spread. The headline value is the survey-weighted median across views, which gives each expert an equal vote in line with a median-voter rule (Hänsel et al. 2020).

Each resulting weighting schedule is summarized by a constant-rate exponential approximation $\hat{w}(t) = (1 + r_w)^{-(t-t_0)}$, fitted by regressing $-\ln w(t)$ on the horizon $t - t_0$ with the intercept fixed at zero. The fitted discrete-compounding rate r_w of Equation (3.4) follows from the slope, and the quality of the approximation is reported as an R^2 in the same log space.

Within each view, empirical uncertainty is integrated in two ways. The *median (typical state)* aggregation fits a rate to every trajectory–preference combination and takes the median across trajectories within each view. It describes the central case and is robust to the rare high-cost trajectories in the right tail of the distribution. The *certainty-equivalent (expected welfare)* aggregation instead forms each view's schedule from the ratio of mean social costs across trajectories

i,

$$w_j^{\mathrm{ce}}(t) \; = \; \frac{\mathbb{E}_i\left[\mathrm{SCC}_{t_0,ij}(t)\right]}{\mathbb{E}_i\left[\mathrm{SCC}_{t_0,ij}(t_0)\right]}\,, \tag{3.5}$$

and fits the rate to that schedule. This is the welfare-consistent treatment for an evaluator who ranks options by expected welfare, and it matches the convention by which social-cost estimates are reported as Monte Carlo means (Rennert et al. 2022a). The certainty-equivalent rate sits below the typical-state median because the right skew of the social-cost distribution deepens with the emission year, so the trajectories that carry the expectation are those whose weights decline most slowly.

3.2 The ClimFor model (Paper II)

ClimFor is a dynamic forest-carbon and wood-systems model that traces carbon, on a mass-balance basis, from forest growth through harvest, processing, product use, and end-of-life. The model and its full parameterization are documented in Paper II, so this section conveys only the guiding principles.

3.2.1 Overview and system boundaries

The defining feature of ClimFor is a single closed mass balance spanning the entire forest-to-disposal chain, so that carbon is neither created nor lost unaccounted for as it moves between the forest, processing, and use phases. The model is applied to the EU27 with 2020 as the base year, and resolves three regions (North, Central, and South) to capture the wide variation in European forest growth and harvest. Within this scope, it tracks roughly 40 products and co-products, around an order of magnitude finer than prior integrated assessments, which lets the carbon cost be attributed to each individual product rather than to a few lumped classes. Production and use data are compiled from Eurostat and FAOSTAT.

3.2.2 Forest carbon and the no-harvest baseline

The forest is represented by five carbon pools, namely living trees, dead trees, forest floor, soil organic carbon, and logging residues, each updated in annual time steps. Living biomass grows along a Chapman–Richards function and is partitioned into tree components through age-dependent allometric relations, supplying litter and turnover to the dead and soil pools, following a first-order decay function. Growth functions, harvest regimes, and standing stocks are calibrated against national forest inventories and harmonized pan-European datasets (Bukoski et al. 2022; Suvanto et al. 2025; Avitabile et al. 2024).

The central principle of the forestry phase is that the climate effect of harvest is measured against a no-harvest counterfactual, in which the same stand would have continued to accumulate carbon. This captures the opportunity cost of forgone sequestration rather than only the carbon removed at felling. In practice, each region is first spun up to a near-steady unharvested state, after which two parallel simulations, one harvested and one left to grow, are compared.

3.2.3 Products, substitution, and end-of-life

Beyond the forest, carbon is followed through a chain of individual unit processes that convert logs and intermediates into products and co-products, each with its own wood-carbon mass balance. Part of the feedstock is combusted on site to meet process heat demand and returns to the atmosphere within a few years, while the carbon entering products is stored for the duration of each product's service life. Service lives are modelled with a gamma distribution for sawnwood, mass timber, and panels, and with first-order decay for paper, and at end-of-life products are either recycled into new material products or incinerated. These dynamics draw on European processing and material-flow data and IPCC harvested-wood-product guidance (Suhr et al. 2015; IPCC 2019).

When substitution is assessed, it is evaluated within the same framework. ClimFor adopts a marginal, consequential view of displacement, crediting only the fraction of wood output that displaces a non-wood material or fuel at the market level, rather than assuming one-for-one displacement. Climate costs and credits are allocated across co-products by economic value.

3.2.4 From CSC to emission factor

The model's central output is the CSC per unit of output, defined as the time-weighted cumulative annual CSC divided by the time-weighted cumulative output, summed across the forestry, processing, and end-use phases. The CO_2 time-weighting is the welfare-equivalent typical-view schedule of Section 3.1, and wood outputs are weighted on an equally principled method that accounts for relative welfare-value changes between wood products and general consumption. The result is a single base-year welfare-equivalent emission factor for each product, a CO_2-equivalent that treats forgone storage on par with actual emissions

(Section 2.1.1). This factor is the quantity that Paper I subsequently accounts for inside the energy-system model, taken without any substitution credit.

3.3 From product factors to system value (Paper I)

The final step connects the per-product emission factors to the value of bioenergy in a decarbonizing European energy system. Paper I accounts for the CSCs from each feedstock inside a cost-optimizing energy-system model, and asks how the cost-optimal role of bioenergy shifts once those CSCs are internalized.

3.3.1 Extending the emission factors beyond wood

A European energy system draws on a wider set of land-using technologies than the wood products of Section 3.2, so the welfare-equivalent framework is extended to the remaining feedstocks. CSCs for herbaceous and short-rotation woody energy crops are derived from land-carbon loss data (Merfort et al. 2023) combined with separate yield assumptions, while those for crop residues and manure follow from a review of the soil-carbon literature. Sewage sludge and residues from landscape care are assigned a CSC of zero, since their use diverts material that would otherwise decompose without an additional land-carbon loss, and imported solid biomass is assigned a factor based on the composition of import feedstocks.

Every factor is placed on the same welfare-equivalent basis as the wood factors of Section 3.2 – the net CO_2 flux integrated over a long (in principle infinite) horizon at the CO_2 weighting rate of Section 3.1 – so that each feedstock reduces to a single base-year emission factor (the resulting factors are shown for the full feedstock set in Figure 4.6). Processing emissions are set to zero, consistent with a climate-neutral Europe in which fossil-based process energy has been replaced by carbon-neutral alternatives.

Onshore wind and solar are included on the same principle. Both occupy fertile land that can no longer store carbon in an alternative use such as forest, and this foregone storage is itself a CSC. The lost storage on a permanently occupied site is expressed as a welfare-equivalent cumulative carbon loss and, under continuous repowering, converted into an annual land-use emission per unit of installed capacity using an electricity weighting rate set equal to the social discount rate, which in turn is aligned with the CO_2 weighting rate of Section 3.1 via the orthogonal regression between the two rates. Footprint areas are taken from the literature.

3.3.2 Accounting for CSCs in PyPSA-Eur

The emission factors are accounted for within PyPSA-Eur, an open-source, multi-sector optimization model of the European energy system (Hörsch et al. 2018; Brown et al. 2018b). The model co-optimizes investment and dispatch across electricity, heating, transport, and industry within a single linear program that minimizes annualized total system cost, subject to sectoral final-energy demands that enter as inelastic constraints. The version used here resolves Europe into 50 nodes at six-hourly resolution over a representative meteorological year, and adopts a greenfield 2050 snapshot in which only long-lived assets – nuclear, hydro, and the existing transmission grid – are retained, while all other capacity must be built anew. The biomass portfolio is broadened to a diversified set of feedstocks mapped to the ENSPRESO database (Ruiz et al. 2019), all major bio-conversion and carbon-capture chains are activated, and the industrial process-heat sector is endogenized across three temperature bands.

We compare two scenarios. *Default* mirrors current practice, treating biomass and variable renewables as carbon-neutral, i.e. with a CSC of zero. *Carbon Stock Changes* (CSCs) instead accounts for the calculated factor of every biomass feedstock and of wind- and solar-footprint land use, so that each feedstock's land-carbon change enters the balance rather than being set to zero. In both scenarios the CO_2 sequestration potential is held at the model default of 250 Mt, a parameter whose strong influence on the result is examined separately.

3.3.3 Scenarios and uncertainty

The primary analysis contrasts the cost-optimal systems of the Default and CSCs scenarios: how much bioenergy each deploys, in which sectors, and at what total system cost. Two further analyses probe how robust that contrast is to the assumptions behind it.

Parametric uncertainty is addressed with a global sensitivity analysis using a grouped Morris screening method (Morris 1991), chosen for its low computational cost relative to variance-based alternatives. It quantifies how strongly each uncertain input – the feedstock CSC factors and costs, the sequestration potential, and nuclear and electrolysis investment costs – moves the optimal biomass use across its plausible range. The method perturbs one input at a time from many starting points in the input space and records the resulting change in the output, the elementary effect. The reported metric μ^* is the mean absolute elementary effect (Campolongo et al. 2007), expressed in the units of the output. It therefore ranks inputs by the average magnitude of the influence of their full uncertain range on the output variable. A usage threshold is additionally estimated for the feedstocks whose use is most sensitive to their assumed factor, the "swing" feedstocks. This threshold is the CSC factor above which a feedstock drops out of the cost-optimal solution.

Structural uncertainty is addressed with modelling to generate alternatives (MGA) (DeCarolis 2011; Neumann and Brown 2021), which maps the range of total biomass use compatible with near-optimal system costs. By minimizing and maximizing biomass deployment subject to total cost remaining within a small increment of the optimum, and sweeping that increment across a ladder of allowed cost penalties, the analysis traces how much bioenergy the system *could* use without materially raising cost. The width of this near-optimal range serves as a flexibility metric, and indicates how firmly the headline conclusion holds across configurations the model treats as almost equally good.

Chapter 4

Results

The results follow the same order as the methods, because each result is the input of the next. While the detailed results can be found in the appended papers, this chapter serves as a summary of the central findings.

4.1 The CO_2 weighting rate

Paper III derives the rate at which CO_2 emitted in different years is weighted, grounded in the welfare damages that emissions cause rather than in convention. This section reports that rate under central assumptions and then asks what drives its considerable spread.

4.1.1 Under central assumptions, the weighting rate is 0.6% per year

Across the survey-weighted ensemble of expert views and probabilistic pathways (Section 3.1.3), the fitted CO_2 weighting rate for emission years 2025–2100 is 0.60% per year under the median (typical state) aggregation, with an interquartile range of 0.26–1.43% and a 5th–95th percentile range of 0.07–3.15% across expert views (Figure 4.1). The certainty-equivalent (expected welfare) aggregation gives 0.31% per year (interquartile range 0.15–1.01%). It sits lower because the right skew of the social-cost distribution deepens with the emission year, so the expectation is carried by the trajectories whose weights decline most slowly. For the median expert view the ratio of the mean to the median social cost rises from 1.30 for emissions in 2025 to 1.44 for emissions in 2100. The ranges express disagreement between experts. Within any single view the remaining empirical uncertainty is much smaller, with a typical interquartile width of about 0.37 percentage points (the respondent-weighted median across views of the within-view p25–p75 width).

Both headline rates sit well below the corresponding social discount rates. This is because the weighting rate equals the social discount rate minus the growth rate of the conventionally valued SCC, and since a warming climate and a growing economy push marginal damages upward, the rising SCC offsets much of

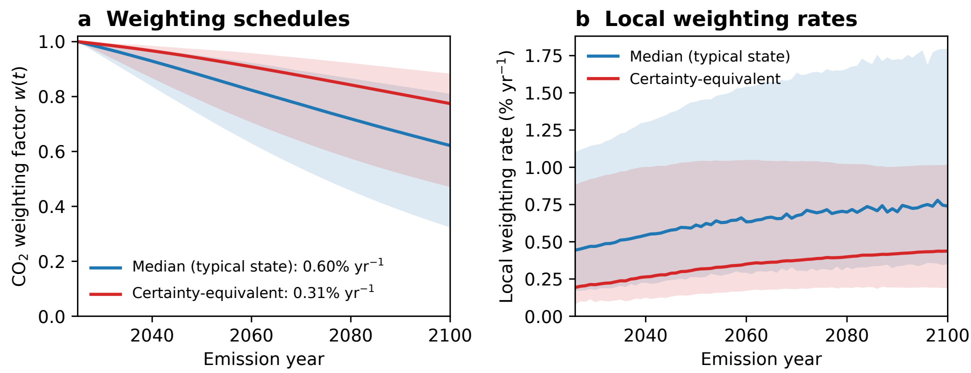


Figure 4.1: CO_2 weighting schedules and local weighting rates under both aggregations. **a**, Weighting factor schedule $w(t)$ for the median (typical state, blue, 0.60%/yr) and certainty-equivalent (expected welfare, red, 0.31%/yr) aggregations. **b**, Implied local weighting rate ($-\mathrm{d}\ln w/\mathrm{d}t$), which rises gently over 2025–2100 under both aggregations. Lines show the median respondent view and shaded bands span the 25th–75th percentile across the 83 expert views of Nesje et al. (2023). Figure from Paper III.

the time discount. A single constant rate captures each schedule closely (median $R^2 = 0.98$ for the median aggregation and 0.99 for the certainty-equivalent), which is what permits carrying a single rate, rather than a full schedule, into the analyses of Papers II and I.

4.1.2 Normative uncertainty dominates

Variation in the fitted rate across the ensemble is almost entirely normative. Regressing the fitted weighting rate on the two Ramsey parameters alone explains 74% of the variance, whereas the pathway descriptors (GDP growth, population growth, and warming in 2100) together explain 4%. The choice of damage function also matters less than the Ramsey parameters. Across linear, quadratic, Howard–Sterner, and cubic specifications, the medians (typical state) span only 0.40–0.88% per year. With a more convex damage function, the influence of warming on the weighting rate grows, raising future damages and thus lowering the rate. However, the interquartile spread across different damage functions is still smaller than the interquartile range of any single specification. The weighting rate is thus not merely an empirical quantity that better climate or growth projections could pin down but requires normative judgement.

Figure 4.2 maps the fitted rate across the Ramsey parameter space, evaluated on a regular (ρ, η) grid over all 10,000 trajectories. Under the typical-state aggregation the rate rises steeply and monotonically along both axes, exceeding 4% per year in the corner of strong normative preferences.

The two parameters do not enter in the same way. A higher ρ raises the social discount rate without changing how fast marginal damages grow, so it pushes the weighting rate up. A higher η raises the social discount rate only in proportion to the growth of consumption, and that same growth also governs the damages being discounted, so what it does to the weighting rate depends on its own value and on the growth projected.

Behind this lies a tug of war between two effects of economic growth. Growth exposes a larger economy to climate damage, so future marginal damages grow roughly with GDP. Growth also raises the social discount rate through the wealth term $\eta\, g_c$ of Equation (3.1). When η is close to one and the population is roughly stable, the two effects cancel and growth barely moves the weighting rate. When η is above one, discounting wins and growth pushes the rate up. When η is below one, the exposure effect wins and growth pulls the rate down. This is also why GDP growth has the largest impact on the weighting rate the further η lies from one.

The same tug of war produces the reversal in the certainty-equivalent rate for views combining high η with low ρ. A high η makes the value of an extra unit of consumption fall steeply as people get richer, so modest differences in growth between trajectories become enormous differences in the welfare cost of damages. The expectation is then dominated by a few trajectories in which consumption stagnates or contracts. In those worlds the discount rate stays low while warming keeps damages rising, so later emissions hurt almost as much as emissions today and the fitted rate stays small. This is akin to the dismal regime of Weitzman (2009), in which the expectation is governed by the tail of the distribution rather than by its typical state. For very low η the tail flips, and the expectation is instead dominated by high-growth, high-damage trajectories.

Because the same normative parameters drive the weighting rate and the social discount rate, the two co-move tightly across expert views (weighted Pearson correlation 0.946). Survey-weighted medians (typical-state aggregation) lie close to the invertible mapping $r_w = \max\big(0,\ (r_s - 1.56)/1.36\big)$%/yr. A practitioner who has committed to a social discount rate can therefore read off the implied CO_2 weighting rate directly.

The typical-state median of 0.60% per year, together with its interquartile range, is the weighting schedule that the rest of this thesis carries forward. The

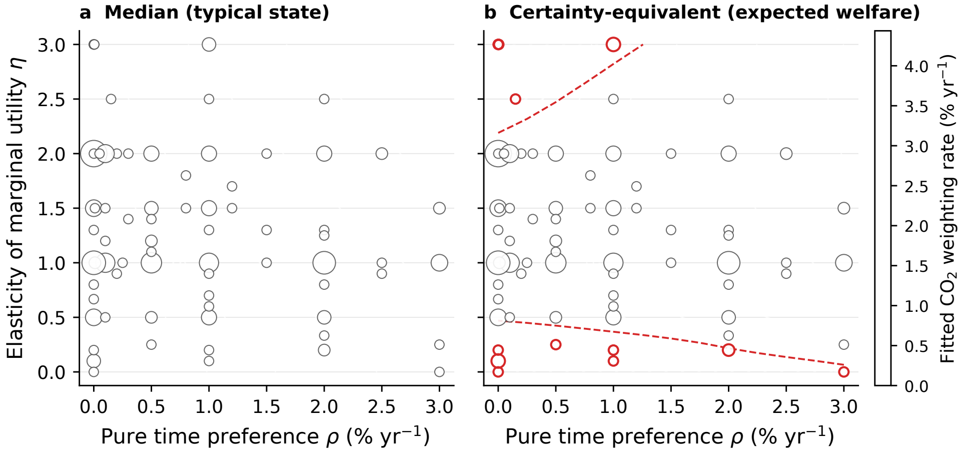


Figure 4.2: Fitted CO_2 weighting rate across the Ramsey parameter space under the median (**a**) and certainty-equivalent (**b**) aggregations, each node evaluated over all 10,000 trajectories. White contours mark selected rates and white circles show the expert-elicited (ρ, η) views of Nesje et al. (2023), with circle area proportional to respondent count. In the hatched regions of panel **b** the top 1% of draws contribute more than half of the base-year mean social cost, marking the tail-dominated regime. Figure from Paper III.

certainty-equivalent alternative is the welfare-consistent treatment of empirical uncertainty, but its value is set by a small set of extreme trajectories. The median is insensitive to that tail and describes the same central case that the forest and energy-system models of Papers II and I represent, making it the consistent choice for the analyses that follow. The next section applies it to the CSCs of the EU forest sector to obtain welfare-equivalent emission factors for wood products, which Paper I then accounts for inside the European energy system.

4.2 The climate cost of EU wood products

Paper III found a central CO_2 weighting rate of about 0.6% per year (for the typical-state aggregation). This section applies that rate to the CSCs of the EU forest and wood system, using the ClimFor model, to obtain a welfare-equivalent climate cost for about 40 individual products and co-products. Each cost is evaluated within a single mass-balanced framework that tracks carbon from forest growth through harvest, processing, product use, and end-of-life, and each is measured against a no-harvest counterfactual in which the same stand keeps accumulating carbon. Paper II reports each product's climate cost both with and without the credit for fossil emissions displaced through substitution. The sector-level results in this section include that credit, whereas the per-unit emission factors carried into Paper I exclude it, so that displacement is represented once, inside the energy-system model (Section 4.3).

4.2.1 The EU wood sector carries a net climate cost

The EU forestry and wood sector imposes a net climate cost of about 165 Mt CO_2 eq per year, with an uncertainty range of 40–390 Mt, rather than the net benefit assumed in most forest policy and life-cycle assessment (Figure 4.3). The dominant driver is CSCs, that is, the forgone forest accumulation relative to the no-harvest counterfactual plus the eventual release of carbon temporarily stored in products. These CSCs alone total about 155 Mt CO_2 eq per year, close to twice the combined fossil-fuel and drained-peatland emissions of the sector. Excluding them, as prior product-level assessments do by treating biogenic CO_2 as climate-neutral, understates the sector's gross climate cost by a factor of two to three.

No end-use category is a net benefit. Construction, packaging, furniture and other materials, and wood fuels are all net costs once the panels they consume are counted alongside sawnwood and laminated timber. Grouped by product rather than by end-use, sawnwood and laminated timber together are the only category that is not a net cost, and even they are merely close to neutral. Laminated timber alone is therefore net beneficial, but it accounts for only about 1% of wood use by mass.

That conclusion holds across the methodological choices tested, although the choices matter a great deal for what the results say about individual products. Moving from welfare-grounded weighting to a 4% discount rate applied to emissions, matching Peng et al. (2023), raises the sector-level impact by about 80% and redistributes it across products (Figure 4.5). Construction timber rises about sevenfold relative to the main estimate whereas wood fuels rise by far less, so timber appears costly relative to fuels, the opposite of the main result. The weighting choice therefore governs the product ranking and not only its magnitude. Removing the no-harvest baseline instead lowers estimated costs by roughly a third, but it does so fairly uniformly across feedstocks, changing the level without changing the ranking. Under no combination of baseline, time-weighting, and substitution treatment tested does the sector cease to be a

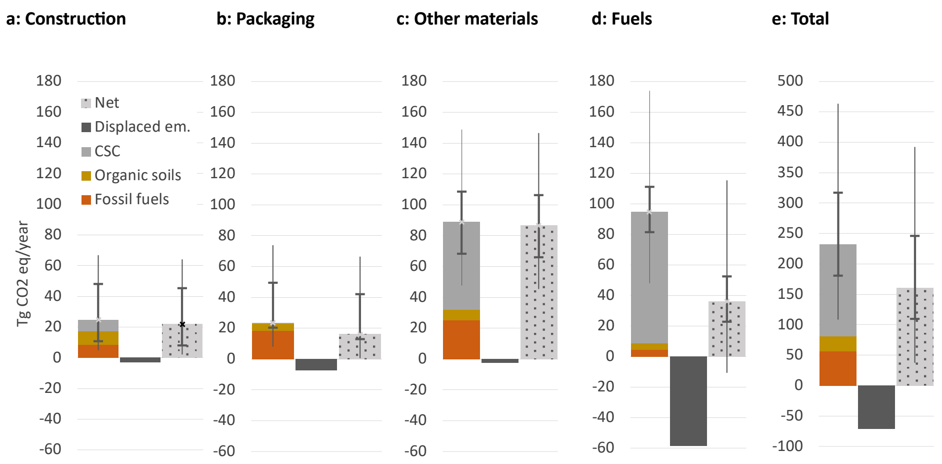


Figure 4.3: Net climate cost of the EU forestry and wood sector by end-use category, including displaced emissions from substitution. Each panel disaggregates the full-sector impact into the total climate impact from fossil fuels, drained organic soils, and CSCs, the displaced emissions from substituting cement, steel, and other fossil-based materials and fuels, and the net impact after substitution. **a**, Construction. **b**, Packaging. **c**, Furniture, cabinetry, and other materials. **d**, Wood fuels. **e**, Total across all end-uses, on a different vertical scale. Values are Tg CO_2 eq per year, equivalently Mt CO_2 eq per year. Thick capped error bars span uncertainty in forest carbon dynamics, service lives, and recycling rates, and thin uncapped bars add the sensitivity to the 25th and 75th percentile time-weighting rates. Figure from Paper II.

net source.

4.2.2 Harvested carbon reaches the atmosphere faster than the forest regrows it

The large CSC component reflects a mismatch in timescales, since harvested carbon returns to the atmosphere far sooner than the forest can rebuild the stock lost at harvest (Figure 4.4). At sector level about 70% of the annually harvested biomass is combusted somewhere in the chain each year, in processing, as fuel, or at end-of-life, so only about 30% is added to in-use product stocks, most of it in short-lived uses such as packaging, paper, and furniture.

The carbon-weighted mean residence time of harvested carbon before release is only about 12 years, far shorter than the roughly 25 years the harvested forest needs to repay the carbon debt of the felling itself. Even with no combustion at all the harvested forest does not reach parity with the unharvested baseline for about 40 years, because that baseline keeps accumulating carbon throughout, and once combustion losses are included consistent parity is reached only after some 740 years, far beyond any policy-relevant horizon. Averaged over several cutting cycles the harvested forest holds roughly 40% less carbon per hectare than the unharvested baseline.

4.2.3 Product footprints span from net sink to large net source

Climate cost varies substantially across products, governed mainly by three factors, namely the share of feedstock combusted in processing, the average product service life, and the end-of-life recycling rate (Figure 4.5). A common structure underlies all three. Upstream of processing, the forestry phase is itself a net carbon benefit under the central weighting rate, because 0.6% per year still gives considerable weight to the uptake of regrowth decades after the felling. A product's net cost is therefore the sum of that forestry-phase benefit and the downstream releases from combustion in processing and from incineration at end-of-life, and what separates products is how much of the harvested carbon is burnt and how long the remainder is held.

Sawnwood and laminated timber carry the lowest cost per kilogram. Processing combusts only about a tenth of the feedstock, construction service lives exceed 50 years, well beyond the roughly 25 years the harvested stand needs to repay its own carbon debt, and about half of used sawnwood is recycled, so the eventual release is both small and heavily time-weighted. Panels carry the highest cost per kilogram among the material products. Their service lives are shorter, because much panel output goes to furniture and cabinetry rather than to structural elements, and recycling into new material products is negligible, so almost all of the carbon is eventually incinerated. Paper sits between the two. Chemical pulping combusts about 60% of the feedstock, giving paper the highest processing emissions of any category, but a recycling rate of about 73% keeps the eventual release low despite a service life of under two years.

Wood fuels stand apart. On carbon stock alone they are by far the largest source in the sector, since combustion returns every unit of fixed carbon within the year of harvest, and per unit of energy fuel pellets and fuelwood exceed or come close to the climate cost of fossil gas including its upstream emissions. The exceptions are logging residues and salvage-logged trees, for which the counterfactual is decomposition in place over roughly a decade.

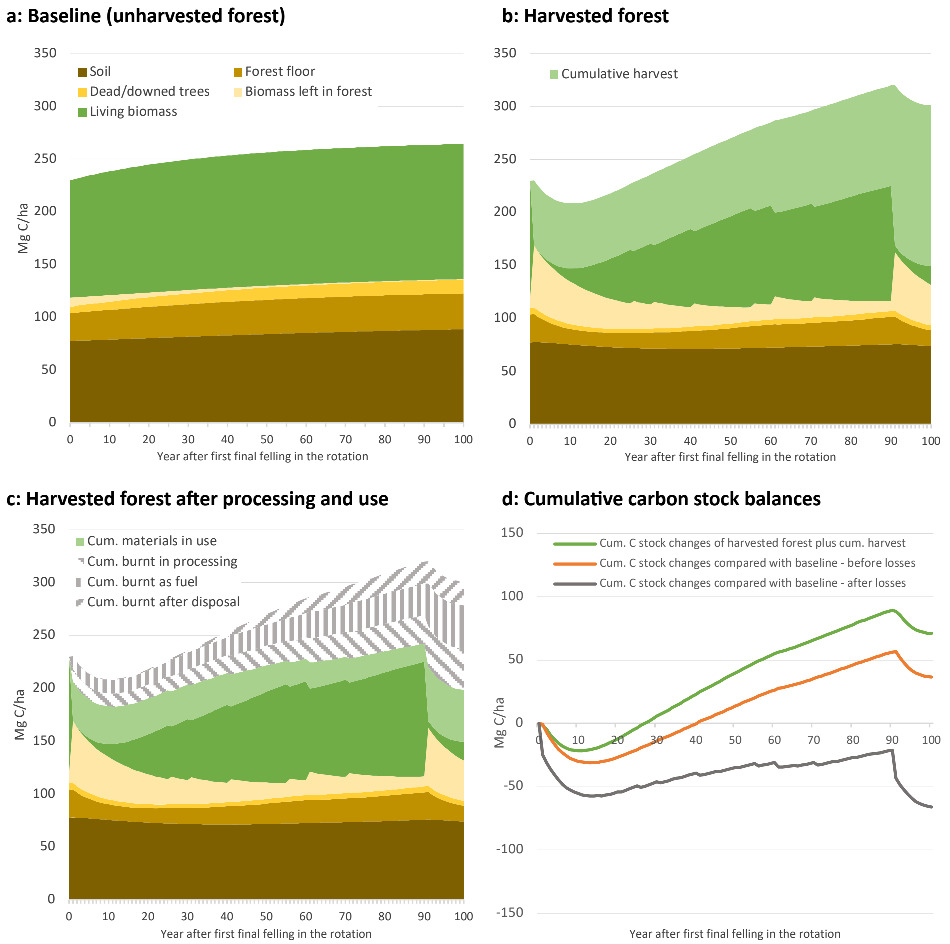


Figure 4.4: Modelled forest carbon stock dynamics and balances, in Mg C per hectare, over 100 years after the first final felling, for the EU average around 2020. **a**, Baseline unharvested forest. **b**, Harvested forest including cumulative harvested wood. **c**, As **b**, but also showing losses of harvested carbon through burning in processing, use as fuel, and end-of-life incineration. **d**, Cumulative carbon balances. The harvested forest including cumulative harvest becomes a net sink within about 10 years and repays its felling debt in about 25 years (green). Compared with the counterfactual baseline, parity of this pool is reached in about 40 years (red). After losses, the balance stays negative for centuries and consistent parity is reached only after about 740 years (grey), beyond the plotted window. Figure from Paper II.

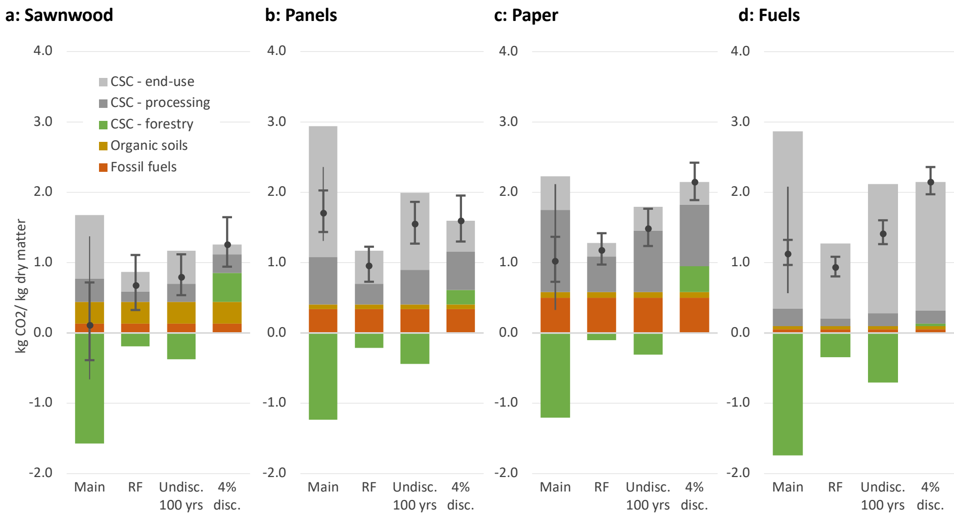


Figure 4.5: Climate impact per kilogram of dry matter for the major wood-product categories, in kg CO_2 per kg, averaged across products within each category and shown before the substitution credit. Stacked bars show contributions from fossil fuels, drained organic soils, and CSCs in the forestry, processing, and end-use phases. **a**, Sawnwood. **b**, Panels. **c**, Paper and carton. **d**, Wood fuels. Each panel shows the main welfare-grounded estimate alongside a radiative-forcing estimate, an undiscounted 100-year estimate, and a 4% discount-rate estimate. Thick capped error bars span uncertainty in forest carbon dynamics, service lives, and recycling rates, and thin uncapped bars add the sensitivity to the 25th and 75th percentile time-weighting rates. Figure from Paper II.

4.2.4 Substitution offsets about 30% of the gross climate impact

Substitution credits from displacing fossil materials and fuels offset about 30% of the sector's gross climate cost, which is not enough to make the sector benign. Total displaced emissions of about 72 Mt CO_2 eq per year fall short of the roughly 82 Mt the sector emits from fossil combustion and drained soils, so substitution does not neutralize even its direct recurring emissions before any CSC is counted. The credit is also concentrated where the carbon cost is highest rather than where the policy debate places it. Wood fuels supply about 82% of all displaced emissions, whereas construction sawnwood and laminated timber together contribute under 4%.

The displacement factors behind that credit are several times below the prevailing literature. Sawnwood replacing masonry is credited at 0.15 t C per t C and mass timber replacing reinforced concrete at 0.28, against published central values of about 1.0–1.3. The lower values follow from current EU emission factors for the substituted materials, which include a carbonation-uptake credit for concrete and the high recycled-scrap share of EU rebar production, and from mass-to-mass substitution ratios taken from paired building studies. Reaching that meta-analytic mean (Leskinen et al. 2018) would require displacing roughly three times more concrete per kilogram of timber than the paired building studies support. The published estimates are also hard to check. Of 186 displacement factors from 65 studies mapped in Paper II, only about 1% report the three components needed to verify them, and about a third ultimately trace back to a single source, Sathre and O'Connor (2010), whose contested average is discussed in Section 2.1.2.

4.3 The system value of bioenergy

This section presents the key results from Paper I, namely how internalizing CSCs alters the role of bioenergy in a carbon-neutral European energy system.

4.3.1 Several woody feedstocks carry fossil-scale emission factors

Paper II converts the CSCs of each forest feedstock into a welfare-equivalent emission factor, using the 0.60% weighting rate of Section 4.1. The resulting factors are substantial, and every forest feedstock but logging residues carries a higher emission factor than natural gas (Figure 4.6). Fuel pellets carry 72 g CO_2/MJ, sawdust and woodchips 69 g CO_2/MJ, and stemwood 68 g CO_2/MJ, against 55 g CO_2/MJ for natural gas and 71 g CO_2/MJ for oil. Of the fuels

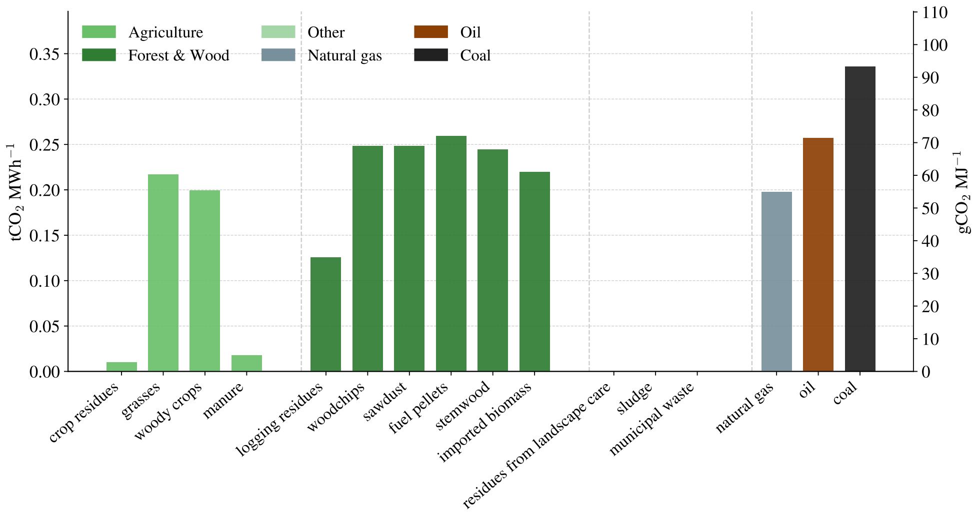


Figure 4.6: Welfare-equivalent CSC emission factors for the biomass feedstocks represented in the energy-system model, grouped by category (agriculture; forest and wood; and other), with natural gas, oil, and coal shown for comparison. Factors are expressed as CO_2 per unit of delivered energy: t CO_2/MWh on the left axis and g CO_2/MJ on the right. Every forest feedstock but logging residues carries a factor above natural gas, and fuel pellets, sawdust, woodchips, and stemwood approach or exceed oil, while the low-carbon residues (landscape care, sludge, municipal waste) sit near zero. Figure from Paper I.

shown, only coal is more carbon-intensive, at 93 g CO_2/MJ. The fossil values are combustion emissions, so the margin over natural gas narrows once the upstream emissions of gas are counted, as they are in Section 4.2. These values arise mainly from the land-carbon loss at harvest, which is essentially the carbon content of the biomass. The CO_2 weighting rate of 0.6% still gives future uptake considerable weight, however, so the factors are less extreme than they would be at a higher rate.

These factors enter the energy-system model PyPSA-Eur in the CSCs scenario, which is compared against a Default scenario that treats biomass as carbon-neutral in the conventional manner. Both scenarios use the model's default CO_2 sequestration potential of 250 Mt per year.

4.3.2 Counting CSCs halves cost-optimal biomass use

Internalizing CSCs reduces cost-optimal biomass use by 52%, from 2,600 TWh in the Default scenario to 1,254 TWh in the CSCs scenario.

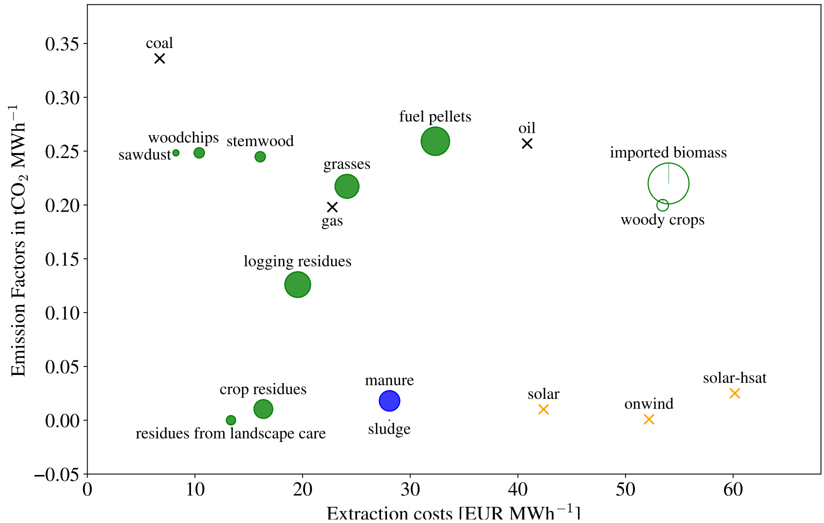
Once land carbon is accounted for, the system cost of each feedstock rises in proportion to its emission factor, and the high-carbon woody feedstocks become uncompetitive (Figure 4.7). Stemwood and the stemwood-derived processing residues (fuel pellets, sawdust, woodchips) leave the cost-optimal mix, together with both dedicated energy crops (grasses and short-rotation woody crops). The feedstocks that remain are crop residues, residues from landscape care, manure, sludge, and logging residues. These are feedstocks whose use diverts material that would otherwise decompose or be disposed of anyway, carrying little or no forgone land carbon.

The feedstocks that remain in use become considerably more valuable. With low-carbon biomass scarce and demand for carbon-containing fuels persistent, the marginal value of residues from landscape care rises by 127% and that of crop residues by 114%, while sawdust, woodchips, and stemwood lose between 64 and 78% of theirs. Two forces pull in opposite directions. Scarcity rents raise the value of the limited low-carbon feedstocks, while a carbon-budget penalty that grows with the CO_2 shadow price erodes the value of everything carbon-intensive.

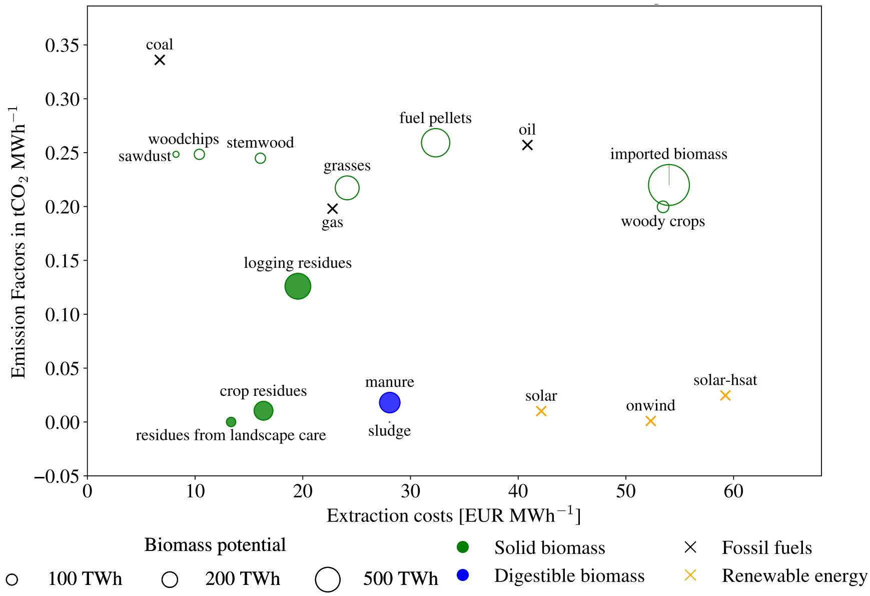
The system as a whole also leans on biomass far less. Removing bioenergy entirely raises total system cost by 19.6% in the Default scenario but by only 8.5% in the CSCs scenario. The near-optimal solution space does not measure marginal value directly, but it does indicate how strongly the cost-optimal system depends on biomass, and that dependence more than halves once land carbon is counted. Much of the apparent indispensability of biomass under the carbon-neutral convention therefore does not survive the change in accounting. Total annualized system cost rises from 784 to 870 billion euros (2025 prices) between the two scenarios, and the lower biomass use avoids 322 Mt CO_2 of land-carbon loss in 2050, more than the EU's 2030 net-removals target for the land-use sector (LULUCF) of 310 Mt CO_2-eq (European Parliament and Council of the European Union 2023c).

4.3.3 Wind, solar, and carbon capture replace biomass

Biomass is replaced primarily by wind and solar power, whose land-use CSCs are small. Wind capacity rises by 47%, adding 1,002 TWh of generation, and solar capacity by 22%, adding 574 TWh (Figure 4.8). Further substitutes are the



(a) Default



(b) Carbon Stock Changes

Figure 4.7: Feedstocks and their fossil and renewable alternatives placed by supply cost (horizontal) and CSC emission factor (vertical). Circle area is the technical energy potential and the filled fraction is the share of that potential the cost-optimal solution uses. In the Default scenario almost every feedstock is drawn on to its potential, whereas in the CSCs scenario the circles in the upper band empty out and only the low-factor residues along the bottom stay in full use. Figure from Paper I.

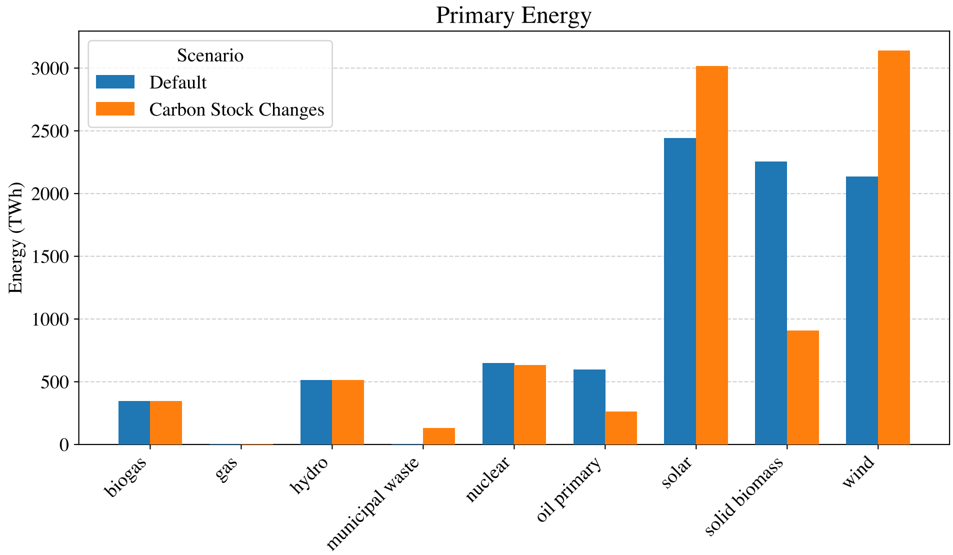


Figure 4.8: Primary energy production in the Default and Carbon Stock Changes scenarios. When CSCs are internalized, wind and solar power replace most of the withdrawn biomass, with wind generation rising by 1,002 TWh and solar by 574 TWh. Figure from Paper I.

electricity-coupled technologies that integrate variable renewables, namely heat pumps, grid expansion, and storage, together with expanded direct air capture and CCS.

4.3.4 The CO_2 sequestration potential defines the budget for linear emission flows

Accounting for land carbon means biomass must compete for scarce permanent CO_2 storage. Carbon in a net-zero system moves along two pathways. The linear flow covers emissions from fossil fuels, cement, and high-CSC biomass, which must be balanced by an equivalent amount of permanent storage. The circular flow covers captured carbon that is resynthesized into fuels and re-emitted, adding no net CO_2. The sequestration potential caps the linear flow and therefore limits how much fossil fuel and high-carbon biomass the system can use.

Cost-optimal biomass use stays at 1,254 TWh across sequestration potentials from 710 down to 200 Mt per year, and falls to 982 TWh at 150 Mt. At the default budget the storage ceiling limits how far biomass use can expand under higher cost, but it does not set the cost-optimal level itself. Only a tighter budget lowers the optimum. The substitution of biomass by variable renewables holds in direction across the full 150–710 Mt range, with wind rising by roughly 370–1,100 TWh and solar by 140–710 TWh as biomass falls by roughly 700–1,630 TWh, though the magnitude shrinks sharply at the highest sequestration potential as fossil gas with CCS enters the mix.

4.3.5 Feedstock emission factors are the primary driver of biomass use

A global sensitivity analysis using the Method of Morris identifies the parameters that most influence biomass use (Figure 4.9). Biomass use is governed primarily by the CSC emission factors of individual feedstocks. The largest effect comes from the CSC factor of logging residues ($\mu^* = 522$ TWh), followed by fuel pellets and grasses. For each of these swing feedstocks, a higher assumed CSC factor reduces its use, which ranges from zero to full potential depending on the assumed factor. The CO_2 sequestration potential ranks only fifth for biomass use, although it dominates fossil-fuel use ($\mu^* = 1{,}596$ TWh for fossil gas). Feedstock cost has a more moderate effect on biomass use ($\mu^* = 108$ TWh).

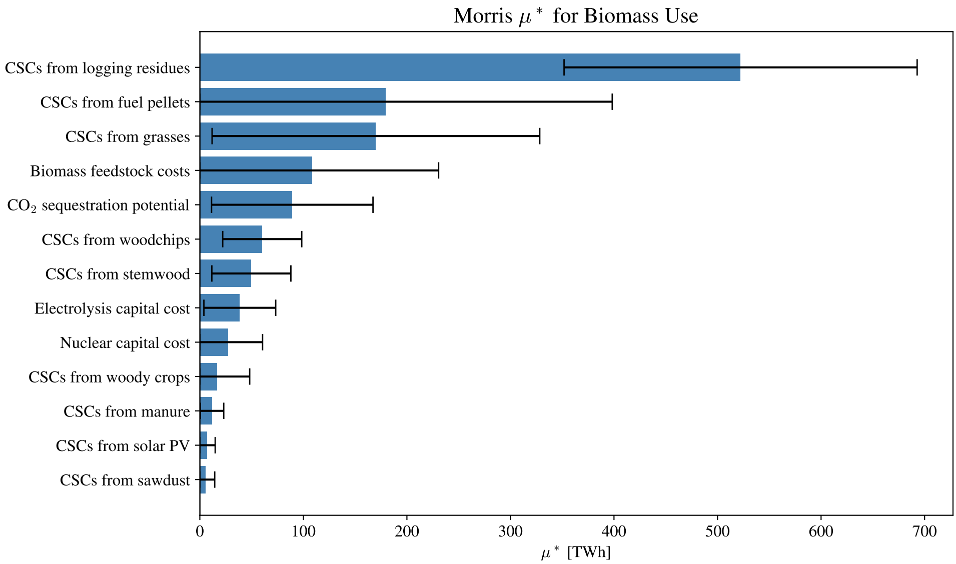


Figure 4.9: Mean absolute elementary effects (μ^*, in units of the output) on total biomass use. Biomass use responds most strongly to the CSC emission factors of individual feedstocks, led by logging residues ($\mu^* = 522$ TWh), while the CO_2 sequestration potential ranks only fifth. Figure from Paper I.

Chapter 5

Discussion

While the focused discussions of the paper-specific results sit in the appended papers, my aim here is to draw out the overarching findings. I focus on cross-cutting themes, on what this work means for the larger research context, and on how it can motivate future research.

This thesis shows that being more rigorous about assessing the consequences of our actions can change how we should make decisions – if we want to maximize welfare. Analysing how the timing of emissions actually affects our collective well-being changes how we weight them. Analysing how biomass harvest actually affects carbon stocks alters the carbon footprints we assign to wood. And accounting for those footprints in an energy system that must decide how much biomass to use changes its optimal configuration.

The analyses are also linked, so that upstream changes propagate downstream. A change in the normative parameters that set the social discount rate, and thereby the CO_2 weighting rate, alters the conclusions further down the chain. For some feedstocks, the emission factor sits close to the value at which the energy model switches them in or out of the energy mix, so a small change in the carbon footprint is enough to tip the balance. As Paper III shows, normative uncertainty is the most influential of all. Which biomass feedstocks appear as valuable to use, therefore, hinges on how we think about the welfare value of consumption and of future generations.

What complicates this further is that the question of how to deal with uncertainty is itself normative. It includes how averse we are, or should be, to risk, and how we handle disagreement. It includes whether we give every view an equal *vote*, which amounts to choosing the median position, or an equal *weight*, which amounts to taking the mean and granting extreme but less frequent positions extraordinary decision power.

All of this shows that – at least in this instance – we cannot sever decisions from their normative dimension in the usual descriptive manner of climate-related science. As the comparison of conventional rates and horizons against the welfare-grounded result showed earlier, attempts to side-step the normative question do not remove it but answer it by convention, and the answer that convention supplies need not correspond to the preferences of those taking the decision, or those affected by it. As Herbert Simon pointed out as early as 1947 (Simon 1947), decisions necessarily contain some form of value judgement. Putting normative parameters into the equations (as done here through the Ramsey parameters), therefore, does not impose a normative layer but brings an existing one to the foreground, where it is open to scrutiny and analysis.

Despite considerable disagreement over normative positions and uncertainty about how the world will change, the three papers still support some robust conclusions.

The first is that delaying CO_2 emissions is always beneficial, which mirrors the finding of Groom and Venmans (2023). The extent to which the welfare-based analysis suggests down-weighting future emissions, however, is much smaller than the social discount rate, precisely because we expect damages to grow over time. The precise rate for weighting CO_2 emissions over time hinges mainly on normative parameters and the choice of how to deal with disagreement, with economic growth becoming more influential once the elasticity of the marginal utility of consumption diverges from 1 and warming becoming more influential the more convex the assumed damage function is.

The second conclusion is that harvesting wood always carries a carbon cost at the site of the forest, because extracting wood extracts carbon from it and disturbs its carbon pools. The weighting rate governs how much of that debt is repaid by regrowth, but carbon neutrality arises only over infinite horizons and only with a CO_2 weighting rate of zero. Downstream effects such as substitution of fossil fuels, long carbon storage in wood products, or even market dynamics that would lead to afforestation can still make harvesting wood the lower-emitting option once the full chain is counted, but they do not change the fact that the act of harvesting leads to a reduction in carbon stocks at the forest level. Overall, our analysis shows that the forest sector today is a net emitter across a large range of normative and epistemic assumptions.

The third conclusion is that, while the precise value of bioenergy hinges on the specific carbon footprints of the feedstocks, the cost-optimal role of bioenergy is consistently smaller once CSCs are accounted for. Neglecting them overestimates its system value. Forest-based biomass, in particular, except for logging residues, falls out of the energy mix across a wide range of assumptions.

5.1 Policy implications

These results do not prescribe a policy. They indicate what a policy would have to represent if the carbon consequences of biomass use are to bear on which feedstocks are chosen. Since the mix is decided by relative feedstock prices, those consequences have to be priced somewhere along the chain rather than merely recorded in the land-sector accounts. Whether such a price reaches the party choosing the feedstock is the decisive question, and Section 2.3.2 sets out the critique that the current arrangement leaves it currently unpriced.

The efficient point at which to levy such a price is arguably the source, since that is where the CSC arises and where the margins that could alter it lie, among them rotation length, species, and which stands are cut. A price on the stock change at harvest, at the rate applied to fossil carbon, would be capitalized in the wood price. It would then reach the energy sector without any separate factor, and it would fall on the biomass whatever it is used for, whereas a charge attached to one end use reaches only that use. The integrated assessment literature indicates what the difference is worth. Where land and fossil carbon are priced together, the effective emission intensity of used biomass is a fraction of what it is where fossil carbon is priced alone (Wise et al. 2009; Merfort et al. 2023).

A restriction on the feedstocks carrying the highest CSCs could be a second-best alternative. Paper I indicates which those are. Once CSCs are counted, stemwood and its processing residues leave the cost-optimal mix, together with the dedicated energy crops, while the residues that divert material which would otherwise decompose remain. A restriction is, however, the blunter instrument. It fixes that margin in advance instead of letting relative costs place it, so it cannot adjust as costs, technologies, or the factors themselves change, and it has to be set from factors that carry substantial uncertainty. How tight it should be depends, moreover, on the weighting rate, which is normative and which Paper III makes explicit rather than resolves.

Ranking these options against one another would require the land-side responses that Paper I holds fixed, and beyond that a judgement on practicality and political support that this thesis cannot supply.

5.2 Reflections and limitations

For the three attached papers, I made a series of methodological choices that define the results and their meaning. In this section, I will reflect on the major ones, the alternatives I set aside and the limitations that stem from the methods chosen.

5.2.1 Paper III: the welfare basis for time-weighting

For Paper III, to answer the question of how emissions should be weighted over time, I chose a welfarist approach. The honest reason is that I think welfare is what climate decisions are ultimately about. Another reason is transparency. The choice of a basis for weighting is normative in nature, and any weighting scheme must answer the question of what matters and when. A welfarist scheme answers it explicitly rather than arbitrarily. It is not the object of this thesis to defend utilitarianism philosophically, but I acknowledge that this prior commitment underlies the choice of methodology and its consequences. In the scientific context, it means that I follow the logic of the social cost of carbon and inherit its controversies, which can be summed up as structural oversimplification of climate damages (Pindyck 2013; National Academies of Sciences, Engineering, and Medicine 2017) and normative contestation, primarily over discounting and interpersonal aggregation (Nordhaus 2007; Stern 2008).

An obvious alternative to welfare-based weighting is a purely physical basis, such as radiative forcing or temperature change. Reasons why this approach might seem attractive are that it does not change the objective realities of emissions or radiative forcing. A physical approach is grounded in scientific measurement rather than relying on controversial discount rates. A physical basis does not distort the amount of emissions and can be easily aligned with climate targets, and it is easy to be made transparent.

On the downside, integrating forcing or summing emissions requires an arbitrary time horizon fixed by convention, which leads to implicit discounting choices that are detached from the actual damages incurred by differently timed emissions (see Section 2.2.2), and changing this convention can arbitrarily change the conclusions.

One could instead adopt a target-based approach, which spans from purely physical metrics such as the GTP (Shine et al. 2005) to target-consistent pricing, which retains welfare-based discounting but replaces the contested damage function with a politically agreed target (Manne and Richels 2001; Stern et al. 2021). Yet both variants share the same weaknesses. The target itself is a normative choice, and everything that happens on the way to it is ignored, including the interim damages that pose much of the motivation for climate policy in the first place. More fundamentally, none of these alternatives avoids the normative question. They answer it implicitly rather than explicitly, a point the IPCC itself makes in noting that the choice of metric and time horizon is a value judgement (Myhre et al. 2013), while target-based approaches relocate the value judgement into the choice of target.

Choosing a welfare-consistent approach does not conceal the normative questions but makes them open to scrutiny and offers flexibility from climate targets. It also connects the weighting of decisions to what people ultimately care about, namely how they influence their well-being. However, the method brings with it the challenge of transparent reporting and requires people to understand what the metric is actually saying because a unit welfare-equivalent CO_2 is not the same as a physical emission anymore.

I also acknowledge that – despite extensive integration and analysis of uncertainty – my implementation represents welfare crudely. Refinements could include endogenizing damage feedbacks on economic growth (Moore and Diaz 2015), representing non-market damages and imperfect substitutability (Sterner and Persson 2008; Drupp and Hänsel 2021), accounting for wealth inequality (Dennig et al. 2015), or giving weight to the worse off through prioritarian welfare functions (Adler et al. 2017).

5.2.2 Paper II: the harvest counterfactual and the boundary of responsibility

For Paper II, a central choice is the counterfactual baseline against which harvest is measured, and, as I outlined in Section 2.1.1, this choice is highly contested.

A fundamental problem is that the counterfactual is unobservable. We never see the world in which the stand was left standing, so we have to construct it by making assumptions, and we might be constructing the wrong world altogether. For instance, the stand might not keep growing but instead burn, blow down, or be lost to pests before that carbon is ever secured, so the baseline overstates what was forgone. This limitation is manageable because disturbance can be built in with rates from observation and scenarios. It gets harder when the alternative is not a forest at all. If the land would otherwise have been turned into cropland or settlement, the counterfactual carbon stock is much lower, and sustained harvesting may be part of what keeps the land forested in the first place, or even what grows a forest on ground that was bare before.

This raises two questions worth keeping apart. The first is whether we even know the full chain of dominoes that fall when we decide to harvest. That chain runs out through timber markets and through other people's choices, the indirect land-use change and leakage that the biofuel and forest-offset literatures have argued over for years (Searchinger et al. 2008; Plevin et al. 2014; Cowie et al. 2021).

The second question survives even if we could follow the chain. Supposing we knew it, how far along does responsibility actually run? One option is to follow it all the way, tracing the knock-on effects, like indirect land-use change, back to the decision that set them off. The other is to stop nearer the decision, at the carbon the harvest directly moves, measured against what the stand would have done if left alone.

Law faces the same question of how far to follow a chain that runs through other people, and its take is that a cause and a responsibility are not the same. Almost anything can be a cause, in the sense that the outcome needed it in order to happen, so the law commonly stops at what was reasonably foreseeable. It treats a free and informed choice by a later party as a fresh cause that starts a new chain rather than carrying responsibility back to the original actor, what it calls a *novus actus interveniens* (Hart and Honoré 1985). On that view, the landowner who converts the forest makes their own decision, so the conversion is their responsibility, not the harvester's. The exception is when that later choice was foreseeable, or was the very thing the original decision was meant to bring about, in which case responsibility reaches back to that decision and is at least shared.

When it comes to product footprints, this question is translated into the choice between an attributional and a consequential approach (see Section 2.1.1). While what is ultimately relevant for policy makers is knowing the full chain of dominoes, the net effects caused by a decision, there is a strong argument for using the attributional approach for assigning footprints. Standard practice defines attributional assessment descriptively, as the share of global burdens attributable to a product system. I read it here in the stronger sense of an account of responsibility.

Searchinger et al. (2025) argue that a consequential account of the increased use of small cars could credibly entail a reduction in the use of larger cars. While the world in which smaller cars are used emits less CO_2 than the counterfactual world with larger cars, it would be absurd to claim that driving a small car constitutes a carbon withdrawal. If we assign a carbon footprint to the use of a car, we use an attributional approach, measuring it against the baseline of not using a car at all.

The obvious disanalogy is that not driving is a real option, whereas an unmanaged EU forest is not. An attributional reference, however, need not be a state anyone could bring about. It need only be the absence of the activity whose burden is being assigned, which is why not driving serves as a baseline without anyone proposing to abolish cars. The no-harvest reference is an abstraction of the same kind, and the factor computed against it is an attributional metric rather than a forecast.

I argue that the same logic holds for forests. It highlights the importance of system boundaries and the need to distinguish between evaluating the inherent property of a product and the decision-making between options. This is precisely why it is vital to isolate the immediate carbon footprint of a wood product from its potential substitution benefits or induced market dynamics. If policymakers need to know which decision leads to fewer emissions, they can either conduct a full decision-contingent consequential analysis or compare the discrete attributional footprints of the individual options. This latter approach offers greater flexibility, as only specific links in the causal chain need to be reassessed when evaluating different alternatives.

Paper II follows this logic. It measures the forestry-phase CSC against a no-harvest reference, aligning with recent methodological guidance (Soimakallio et al. 2025; Cowie et al. 2025). Consequently, the harvest is judged against the stand's own forgone growth rather than the wider market response to the felling. By the legal reasoning above, this is the point at which a later land-use decision stops being the harvester's responsibility. Despite anchoring its baseline in this attributional perspective, the paper does not ignore the downstream dominoes. It actively examines substitution effects, even incorporating them into expanded emission factors with a wider system boundary. Deeper, market-mediated dynamics, however, are judged to be empirically small and are therefore deliberately set aside (Lubowski et al. 2006; Searchinger et al. 2025). Should new evidence demonstrate that market dynamics are in fact significant, the attributional emission factors derived here would remain structurally valid, serving as modular inputs for future consequential analyses.

That modularity is not only a matter of tidiness but it is what makes the factors usable at all. In Paper I, the energy-system model determines endogenously which fuels and materials biomass displaces, so a factor that already carried a displacement credit of its own would count that displacement twice, once inside the factor and once in the model's substitution decision. The same applies to any consequential analysis that supplies its own market response. Components can only be recombined without duplication if they arrive separable, which is why the CSC and the substitution credit are computed by different methods and reported apart, even where the sector-level balance combines them, and why the substitution-inclusive factors are decision-support figures rather than product footprints.

Another choice of the same kind concerns residues. Where a feedstock is a residue, the cost assigned to it reflects only the fate the material would otherwise have met, so collectable residues carry little or none of the forgone growth of the stand they come from. That measures the collection against a baseline in which the felling still takes place, which is a conditional baseline of the kind the no-harvest reference is adopted to avoid for stemwood. Residue status is also an economic category rather than a physical one. A flow counts as a residue because it carries no value of its own, and demand is capable of removing that condition, either by making residue revenue bear on whether a stand is felled at all or by moving the boundary between residue and low-grade roundwood as prices rise.

The two treatments differ because the activity being attributed differs. An attributional footprint takes as its reference the absence of the activity to which the burden is assigned. For stemwood that activity is the felling, and the reference is the stand left standing. For a residue it is the collection, and the reference is the material left on site. Assigning residues a share of the forgone growth would therefore not add anything to the account but redistribute it, since the felling is already carried in full by the outputs that occasion it.

What this leaves open is the range over which the residue convention holds. It rests on residue supply following a harvest volume that other markets determine, and it weakens as residue demand grows large enough to bear on the felling decision itself. A system in which residues are among the few feedstocks that remain once CSCs are accounted for is one that tends towards that regime, and Paper I cannot represent the tendency, because feedstock potentials and factors are held fixed. This matters for how far the results reach, since the factor assigned to logging residues is the input to which cost-optimal biomass use responds most strongly (Figure 4.9). Establishing where the boundary of the convention lies would require an endogenous land and market representation.

5.2.3 Paper I: exogenous land and a deterministic snapshot

The natural tool for coupling energy and land is an integrated assessment model (IAM) such as REMIND–MAgPIE or MESSAGEix–GLOBIOM, which lets harvest, prices, and land allocation adjust to the carbon signal inside a single optimization. As set out in Section 2.3.3, that integration is what these models are built for and is a genuine strength. I chose a high-resolution energy-system model (PyPSA-Eur) instead and supplied the CSC factors as fixed inputs. The reason is the question I am asking. Using an energy system model, I can isolate how the energy system responds to the land-carbon signal, and how that response shifts with uncertainty in the signal, which is cleanest when the signal is fixed rather than solved for jointly with the land side. A dedicated energy-system model also gives me the cross-sectoral and hourly resolution that integrated assessment models often trade for their broader scope.

The price of this exogeneity is the loss of feedback. Held constant, the feedstocks, their availability and CSC factors are not affected by price responses or indirect land-use change that a change in biomass demand would cause (Searchinger et al. 2008; Plevin et al. 2014). Among those responses is the shift in residue status set out in Section 5.2.2, which sustained demand could bring about and which fixed factors cannot register. Recovering these channels through a hard-linked land representation would demand more contested parameters, among them the price elasticities of biomass demand and the land-use change it induces, and considerably heavier computation, without, in my judgement, changing the answer to the question posed. I therefore treat full integration as a valuable direction for future work rather than a requirement here.

Another choice is to solve a single 2050 end-state as a deterministic least-cost optimization with perfect foresight, rather than a transition pathway or a stochastic plan. Two limitations follow. The first is that I optimize an independent endpoint rather than a transition, so the configuration I obtain is cost-optimal for 2050 taken on its own and need not be reachable from the infrastructure in place today, nor consistent with current policy. The second is that within each solve, the decision-maker has perfect foresight. Even as I vary parameters and map the near-optimal solution space, no run represents a planner hedging against uncertainty that they cannot resolve.

Both point in a known direction, since formulations that grant more foresight than a real, path-dependent transition affords tend to understate costs and overstate the uptake of new technologies (Keppo and Strubegger 2010). What remains open for my question is whether hedging against that uncertainty would raise or lower the role of biomass, which these runs cannot establish and which motivates the stochastic and robust extensions I set out as future work.

Taken together, these simplifications buy computational tractability and a clean identification of the land-carbon effect, at the cost of the market feedbacks and hedging behaviour. I therefore read the results as the response of an idealized least-cost system to the land-carbon signal, robust in direction across the uncertainty I do span, rather than as a forecast of the transition. Other questions might call for hard-linked or stochastic models.

5.3 Future research

The thesis lays the groundwork for future research to address remaining empirical gaps and explore emerging questions.

One avenue is to expand the WE–CO_2 framework to other greenhouse gases such as methane, which would allow methane emissions to be compared across years and against CO_2 emissions. One could also refine the WE–CO_2 method to endogenize the damage-to-growth feedback, or to include further complications such as catastrophic risk and market and non-market substitutability. From a more ethical and decision-theoretical direction, one could investigate more elaborate treatments of normative uncertainty than taking a mean or a median.

Another direction is to extend the ClimFor model to other regions of the world, or to couple it to a partial-equilibrium forest-sector model. The latter would endogenize forestry market feedbacks, which shape harvest, land allocation, and feedstock prices.

For bioenergy, one could pursue stochastic or robust modelling while including CSCs for biomass feedstocks. This would acknowledge more of the uncertainties and derive optimal or robust strategies in the face of them, rather than tracing how they affect a single deterministic decision. Exploratory modelling could span a large set of worlds and normative views to identify scenarios in which biomass becomes particularly system-relevant even once CSCs are accounted for.

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