The Potential for Bioenergy Coupled with Carbon Capture and Storage to Mitigate Climate Change:

A white paper prepared for DRAX

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Abbreviations and Acronyms

BECCS	bioenergy with carbon capture and storage
CCS	carbon capture and storage
CFP	carbon footprint
CO_2	carbon dioxide
CLT	cross-laminated timber
dLUC	direct land use changes
GHG	greenhouse gas
GWP	global warming potential
iLUC	indirect land use changes
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
LCA	life cycle assessment
LCI	life cycle inventory
LDPE	low-density polyethylene
LU	land use
MgO	magnesium oxide
NCASI	National Council for Air and Stream Improvement
NET	negative emissions technology
OSB	oriented strand board
SAF	sustainable aviation fuel

The Potential for Bioenergy Coupled with Carbon Capture and Storage to Mitigate Climate Change

Executive Summary

We documented the potential climate benefits of bioenergy coupled with carbon capture and storage (BECCS or "abated" electricity production) by comparing the use of forest residues and manufacturing residues in BECCS to alternative uses of this wood fibre. The alternatives considered included bioenergy without CCS (or "unabated" electricity production) from wood pellets and from wood chips and the production of corrugated containers, plates, paper books, sustainable aviation fuel (SAF), biochar, oriented strand board (OSB) sheathing, and their non-wood-based substitutes—plastic envelopes, polystyrene plates, e-books, jet fuel, farmyard compost, magnesium oxide (MgO) board, and fibre cement. To provide additional context, we also explored the theoretical use of sawtimber in BECCS relative to its use as a replacement for steel and concrete in building construction.

Results show BECCS provides the largest climate benefits among all considered feedstocks and uses studied with the only exception being the use of manufacturing residues and pulpwood to produce OSB as an alternative to MgO board or fibre cement. Our analyses also show that the use of residues for bioenergy even without CCS produces climate benefits that are greater than each of the other applications studied (biochar, pulp, and SAF). Because biomass is renewable, can be sustainability sourced, and removes CO_2 from the atmosphere, we conclude BECCS, which can occur in parallel with other wood uses, can play a positive role in efforts to mitigate climate change if it is coupled with the responsible management of forests. Consequently, BECCS should be considered an important use of wood fibre, sitting alongside wood-based products in the wood-use hierarchy when determining the best use of woody biomass, especially considering its finite (though renewable) stock. Additionally, the cascading hierarchy of wood fibre uses requires re-visiting considering the opportunity BECCS provides for permanent carbon removals, with a more nuanced approach to wood-based products and with BECCS treated alongside wood-products and not alongside bioenergy without CCS.

ES Table 1: Summary of results

		Net kg $CO_{2\ eq}$/FU (including biogenic CO_2 emissions and uptake)	
Wood fibre use	**Non-wood-based alternative**	**Static**	**Dynamic**
OSB sheathing	MgO board	-4,104	-4,672
OSB sheathing	Fibre cement	-2,686	-2,734
Abated US electricity (chips)	Residual US electricity	-2,304	No effect
Abated UK electricity (pellets)	Residual UK electricity	-2,107	No effect
Unabated US electricity (chips)	Residual US electricity	-689	No effect
Unabated UK electricity (pellets)	Residual UK electricity	-578	No effect
Biochar	Compost (C,N, P & K)	-464	No effect
Pulp – Plates	Polystyrene Plates	-295	-404
Sustainable aviation fuel (SAF)	Jet fuel	-49	No effect
Pulp – Books	E-book	584	166
Pulp – Corrugated containers	LDPE envelopes	2,361	2,207
Sawtimber portal frame	Concrete	-1,164	-1,413
Sawtimber portal frame	Steel	-1,120	-1,369
Cross-laminated timber (CLT) in 5-story building	Steel	-852	-1,384
Cross-laminated timber (CLT) in mid-rise building	Concrete	-232	-618

Background: The Climate Crisis and the Potential Role of Bioenergy Coupled with Carbon Capture and Storage

Effectively addressing the global climate crisis requires reducing greenhouse gas emissions by replacing fossil fuels and fossil fuel-based products with low-carbon and renewable alternatives. The scientific consensus is that energy sector must reduce emissions by 80-100 percent by 2050.[1] Additionally, limiting the rise in global temperatures to 1.5 degrees Celsius will almost certainly require negative emissions technologies (NETs) to remove greenhouse gases from the atmosphere. Estimates are that 10 Gt/y CO_2 will need to be removed by 2050 and 20 Gt/y CO_2 by 2100.[2,3]

Biomass has the potential to contribute to these solutions in multiple ways: the growth of biomass can remove carbon dioxide from the atmosphere through photosynthesis; and biomass can directly replace fossil fuels in the production of energy and can substitute for emissions-intense materials such as steel and cement. The extent to which biomass will confer significant benefits in addressing the climate crisis depends upon factors such as land management and forestry practices, selective use of the most appropriate biomass feedstocks, and the relative carbon footprint of the processes which capture and sequester carbon in comparison to alternatives.

The potential of bioenergy with carbon capture and storage (BECCS) to play a key role in energy production and greenhouse gas mitigation, due to its potential to permanently remove CO_2 from the atmosphere, was recognized by the Intergovernmental Panel on Climate Change (IPCC) in its 2014 and 2018 reports.[4, 5] However, to not create or exacerbate other environmental problems, implementation of BECCS requires following strict criteria such as those detailed in the UK's biomass strategy. These include protection of biodiversity, forests, peatland, and wetland; preservation of ecosystem services such as soil, water, and air quality; the selection of feedstocks that do not compete with food crops for agricultural land; and ensuring that the greenhouse gas emissions associated with the entire life cycle of BECCS (i.e., production, cultivation, harvesting, transportation, combustion, carbon capture, and storage) are lower than those of fossil-fuel-based energy production and that BECCS offers a net carbon benefit as compared to alternative uses of biomass.[6]

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[1] IEA (2022), World Energy Outlook 2022, IEA, Paris https://www.iea.org/reports/world-energy-outlook-2022, License: CC BY 4.0 (report); CC BY NC SA 4.0 (Annex A).

[2] National Academies of Sciences, Engineering, and Medicine. (2019). *Negative emissions technologies and reliable sequestration: A research agenda*. Washington, DC: The National Academies Press. https://doi.org/10.17226/25259.

[3] IEA (2022), World Energy Outlook 2022, IEA, Paris https://www.iea.org/reports/world-energy-outlook-2022, License: CC BY 4.0 (report); CC BY NC SA 4.0 (Annex A).

[4] Intergovernmental Panel on Climate Change (IPCC). (2014). *Climate change 2014: Mitigation of climate change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (O. Edenhofer, R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel, & J. C. Minx, Eds.). Cambridge, United Kingdom and New York, NY: Cambridge University Press.

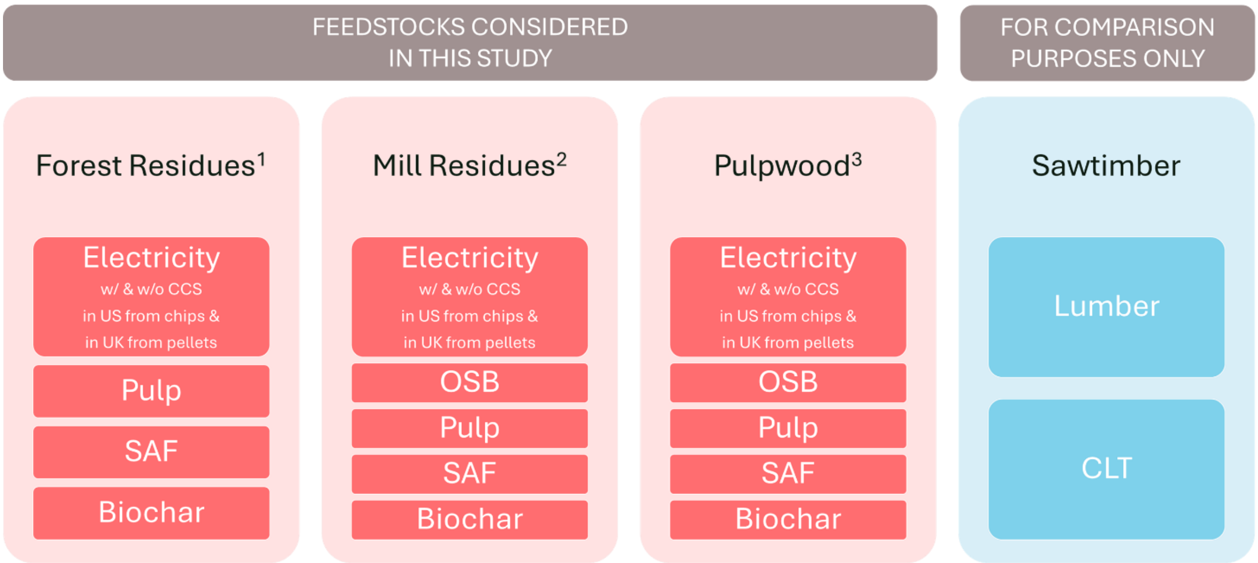
[5] Intergovernmental Panel on Climate Change (IPCC). (2018). Global Warming of 1.5°C.An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty [Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, 616 pp. https://doi.org/ 10.1017/9781009157940.

[6] UK Department for Energy Security and Net Zero. (2023). *Biomass strategy 2023*. Retrieved from https://www.gov.uk/government/publications/biomass-strategy.

Case Study Comparing Bioenergy Coupled with Carbon Capture and Sequestration to Other Wood Fibre Uses

To determine the carbon benefits of BECCS relative to other uses of wood fibre, we conducted a case study that quantified the total life cycle greenhouse gas emissions resulting from BECCS and compared these to the total carbon footprint created from alternative uses of wood fibre. Specifically, we analyzed the cradle-to-energy greenhouse gas (GHG) emissions that result from producing electricity from woody biomass (with and without CCS—i.e., abated versus unabated), sustainable aviation fuel (SAF) and the cradle-to-grave GHG emissions from corrugated boxes, paper plates, paper books, biochar, and oriented strandboard (OBS). We also compared the carbon footprint of sawtimber and cross-laminated timber (CLT) for use in building construction to steel and concrete within the same application. In each application, we assumed the feedstock (i.e., forest residue, mill residue, pulpwood, or sawtimber) used was the type of wood fibre most appropriate to that application (Figure 1). While concern that using wood feedstocks for bioenergy could result in deforestation is valid, this study only considers the use of *existing* feedstocks and *does not promote* the generation of additional feedstocks or make recommendations concerning the management of forests.

Figure 1: Potential BECCS feedstocks and the alternative uses examined



[1]Forest residues are also called harvest residues. [2]Mill residues are also called wood processor residues and include chips, sawdust, and shavings primarily from sawmills. [3]Pulpwood is also called low-grade roundwood.

The Life Cycle Assessment Methodology and the Carbon Footprint Metric

Life cycle assessment (LCA) is a decision support tool used to calculate the environmental impacts of a process or product based on its inputs and outputs. LCAs create a holistic view of a product's environmental performance by quantifying multiple types of impacts from all life cycle stages of a product from raw materials extraction, production, use, and end-of-life. A carbon footprint (CFP) is an LCA focused on the single impact category of climate change that quantifies the sum of GHG emissions and GHG removals in a product system. CFPs are expressed as CO_2 equivalents (CO_2e), with GHG emissions of any type converted to CO_2e using factors that account for the relative heat-trapping ability (or "global warming potential, GWP") of each specific type of GHG. In our calculations, we used the IPCC's 2023 GWP factors[7] for the 100-year timeframe. Because this screening-level study focuses only on the single metric of carbon footprint, conclusions cannot be drawn about the overall environmental performance of the products under study.

The uptake of CO_2 into biomass through photosynthesis removes CO_2e from the atmosphere and creates "biogenic carbon" which is treated as a negative number in CFP calculations. Subsequent emissions of biogenic CO_2—i.e., the release of carbon that had been sequestered in organic matter—is characterized as a positive number in CFP calculations. According to ISO 14067, both fossil and biogenic GHG emissions and removals are required to be included in the CFP calculations and must be documented separately.[8] ISO 14067 also provides guidance about the inclusion and documentation of other types of GHG removals and emissions. However, in this study, GHG removals and emission as a result of land use (LU), direct land use changes (dLUC), and indirect land use changes (iLUC) do not occur, so are not included in the calculated CFP.

To maintain the highest level of rigor and to enable comparability with other past or future studies, we aligned our case study with the four steps outlined in the International Standard for LCA (ISO 14040/44): goal and scope definition, inventory analysis, impact assessment, and interpretation.[9] (See insert for additional information about the four standard steps of an LCA.)

The Four Steps of an ISO-Aligned LCA

1. **Goal and scope definition:** Understand the objectives and intended applications, the boundaries of what is being assessed, and the performance requirement(s) that the product(s) under study fulfil.
2. **Inventory analysis:** Create an inventory of flows to and from nature using a combination of primary and secondary data collected for each unit process of the product system.
3. **Impact assessment:** Apply characterization factors to the inventory to determine the environmental impacts.
4. **Interpretation:** Conduct sensitivity and uncertainty analyses, draw conclusions, and make recommendations

Data Sources, Assumptions, and Modelling Details Used to Ensure Equitable Comparisons

To establish an equitable basis for comparison between all alternative uses of wood under study, we set "the use of 1 dry tonne of wood feedstock" as the common denominator (or "functional unit") and set the boundaries for each product system as starting at the point where wood feedstock is made available for use and ending at the point of product disposition ("grave") or, in the case of energy applications, at the point of combustion. Activities further upstream were excluded from the comparisons because we assumed these were the same in all scenarios. We also considered the carbon footprints of the avoided products and applied allocation in instances of multifunctionality. Details about the pathways of fibre use explored are provided in Table 1, and a generic diagram that depicts the system boundaries in relation to biogenic CO_2 is provided in Figure 2.

[7] GWP values sourced from the literature may have been calculated using an earlier IPPC report; we did not alter these.

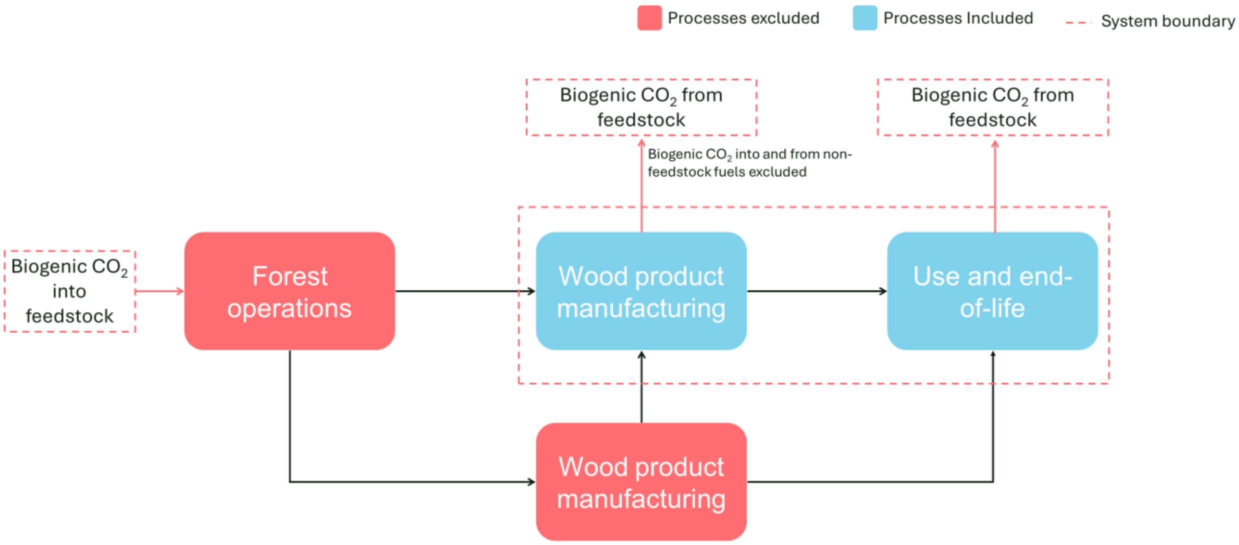
[8] International Organization for Standardization. (2018). *ISO 14067:2018: Greenhouse gases — Carbon footprint of products — Requirements and guidelines for quantification.* Geneva, Switzerland: International Organization for Standardization.

[9] International Organization for Standardization. (2020). *Environmental management – Life cycle assessment – Requirements and guidelines (ISO 14044 Amendment 2).* Geneva, Switzerland: International Organization for Standardization.

Table 1: Alternative pathways for uses of wood fibre

Product pathway	Reference flow	Additional FU	Counterfactual	Reference flow
Electricity in the UK (from chips, w/o BECCS)	0.96 t	1.99 MWh	Residual UK Electricity	1.99 MWh
Electricity in the UK (from chips, w/ BECCS)	0.96 t	1.70 MWh	Residual UK Electricity	1.70 MWh
Electricity in the US (from chips, w/o BECCS)	1 t	1.55 MWh	Residual US Electricity	1.55 MWh
Electricity in the US (from chips, w/ BECCS)	1 t	1.29 MWh	Residual US Electricity	1.29 MWh
OSB	0.83 tonne (0.80 t, fibre only)	Sheathing for 15.6 m^3 house	Fibre Cement	1.42 t
OSB	0.83 tonne (0.80 t, fibre only)	Sheathing for 15.6 m^3 house	MgO Board	1.10 t
Pulp – Corrugated containers	1.6 t	2,540 Packages	LDPE Envelopes	0.15 t
Pulp – Plates production	0.49 t	29,747 Plates	Polystyrene Plates	0.32 t
Pulp – Books	0.4 t Paper	667 Books	E-book	0.007 t
Sustainable aviation fuel (SAF)	0.036 t SAF	3,103 MJ	Jet fuel	0.072 t
Biochar (pyrolysis)	0.16 t	116 kg C, 3.2 kg N, 1.1 kg P, 2.8 kg K	Compost (C,N, P, K)	0.64 t
Sawtimber	0.75 t Sawtimber 0.12 t Steel 0.35 m^3 Concrete	0.045 Portal Frame (10 m)	Steel	0.35 t
Sawtimber	0.75 t Sawtimber 0.12 t Steel 0.35 m^3 Concrete	0.045 Portal Frame (10 m)	Concrete	0.37 m^3
Cross-laminated timber (CLT)	0.76 t	0.10% 5-Story Office Building	Steel	0.24 t
Cross-laminated timber (CLT)	0.76 t	0.087% Mid Rise Building	Concrete	3.74 t

Figure 2: Generic flow diagram for the product pathways studied



Electricity Production in the US from Chips and the UK from Pellets, with and without CCS

To model electricity production in the US, we obtained primary data from Drax. In this process, the bioenergy feedstock is transported from its point of generation to the site of electricity generation by truck. In some cases, this wood would already be in the form of chips (e.g., from sawmills); in other cases, it requires chipping prior to burning. We assumed that the level of processing would be the same for all uses of wood feedstocks, so did not include the chipping process. [In practice, different uses of wood might require different levels of processing, so we conducted a sensitivity analysis to assess the effects of this assumption.] Upon arrival at the power plant, wood chips are screened to remove any foreign objects and are stored in a silo until they are burned in a boiler. Within the boiler, the resultant high-pressure steam spins turbines connected to generators that produce electricity.

For electricity production in the UK, the bioenergy feedstock is delivered to the pellet mill by truck where it is stored in a wood yard or directly processed. Low-grade roundwood is debarked and chipped; whereas other wood feedstocks do not require processing because they are already in the form of chips. (Although this processing would occur irrespective of wood use pathway, energy for doing so was included in the system boundary because it is part of the pellet mill operations and could not be separated out.) Wood chips are screened for quality, and wastes (such as sand, bark, and stones) are removed. Next, the wood chips are dried in a furnace powered by the bark produced in the debarking stage, then are fed into a hammer mill where they are pulverized. The resultant powder is forced through a grate with small holes at high pressure, generating sufficient heat to bind it into compressed pellets. The pellets are sent to cool before transport via rail to a port for overseas shipping. Upon arrival in the UK, wood pellets are delivered by train to a Drax power plant where pellets are screened to remove any foreign objects and are stored in a silo. Pellets are extracted into the fuel pellet pipes, blown through pipes by an air blower, and conveyed to the boiler house from where they are fed into hollow balls, crushed into a fine powder, and blown into a boiler. In the boiler, the powder is burned to generate high-pressure steam that spins turbines connected to generators that produce electricity.

At electricity plants equipped with CCS, (1) flue gas leaving the power production process is (2) cooled and treated before (3) entering an absorption tower where a chemical reaction extracts CO_2 from the air stream and CO_2-depleted flue gas is released to the atmosphere. (4) Within a boiler, the reaction is reversed, separating the CO_2 from the solvent which can then be (5) recirculated back into the carbon capture system. In the UK, the liberated CO_2 will be (6) transported via pipeline for permanent storage under the southern North Sea. (Figure 3 provides a schematic of the CCS process). CO_2 from the natural gas used in CCS is not captured. Because there are currently no operational CCS systems in the US, Drax' US design data was used. A summary of data sources for electricity production is provided in

Table 2.

Figure 3: Diagram of the Drax CCS process

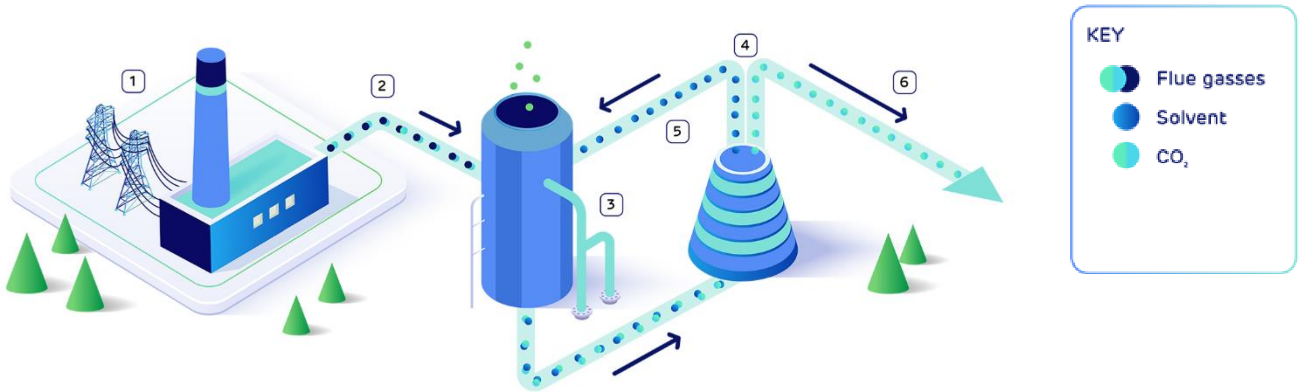


Table 2: Data sources for electricity production processes

Process	Data Source
Electricity production from chips in the US	Drax US design data
Electricity consumption at chip plant in US	ecoinvent 3.10 's US grid mix after correcting for RECs using data from Green-e
CCS in the US	Drax US design data
Pellet production	Amite Pellet Plant
Electricity consumption at pellet plant	ecoinvent 3.10's UK grid mix
Electricity production from pellets in the UK	Drax Power Station (Selby)
CCS in the UK	Drax Power Station (Selby) design data

Corrugated Containers, Paper Plates, and Books from Pulp

Corrugated containers were selected as a use of wood pulp because prior research shows these perform significantly worse than low-density polyethylene (LDPE) envelopes. Paper plates were explored as an alternative use because prior research shows these perform the same as or better then polystyrene plates.[10] E-books were compared to physical paper books because books are a third very common use of wood pulp.

For the corrugated boxes, the wood-to-corrugated product ratio is based on 2020 US Corrugated LCA[11] without recycled content. We calculated the total number of uses (0.5 + 1.25) based on ISO 14049[12] assuming a recovery rate of 90% and a recycling yield of 91%, assuming fibre can be recycled five times, and assuming OCC is recycled only in corrugated. For the kraft paper at end-of-life, we assumed 80% recycled, 16% landfilled, and 4% incinerated. As there are no data available for envelopes from 100% virgin inputs, we modeled their cycle using a mix of average and 100% LDPE. For the end of life, we assumed the envelopes were 80% landfilled, 20% incinerated, and 0% recycled.[13] To determine the equivalency between the corrugated boxes and LDPE envelopes, we relied on data from Franklin and Associates.[14]

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[10] National Council for Air and Stream Improvement (NCASI). (2020). *Review of life cycle assessments comparing paper and plastic products* (NCASI White Paper). https://www.ncasi.org/wp-content/uploads/2020/11/WP-20-09_Plastic_vs_Paper_LCA_Review_Nov2020.pdf.

[11] National Council for Air and Stream Improvement, Inc. (NCASI). 2023. 2020 Life Cycle Assessment of U.S. Average Corrugated Product – Final Report. Report prepared for the Corrugated Packaging Alliance (CPA). Cary, N.C.: National Council for Air and Stream Improvement., Inc. https://www.fibrebox.org/assets/2024/03/2020_LCA-_Full_Report.pdf

[12] International Organization for Standardization. (2012). *ISO 14049: Environmental management — Life cycle assessment — Examples of application of ISO 14044 to goal and scope definition and inventory analysis*. Geneva, Switzerland: ISO.

[13] U.S. Environmental Protection Agency. (2020). *Advancing Sustainable Materials Management: 2018 Tables and Figures*. Retrieved from https://www.epa.gov/sites/default/files/2021-01/documents/2018_tables_and_figures_dec_2020_fnl_508.pdf#page=43&zoom=100,77,85.

[14] Franklin Associates. (2004). *Life cycle inventory of packaging options for shipment of retail mail-order soft goods: Final peer-reviewed report*. Prairie Village, KS.

For paper plates, we used the wood-to-paperboard ratio in ecoinvent v3.10 and calculated the equivalency between paper plates and polystyrene using data from Franklin and Associates 2011.[15] For the end of life of both plate types, we assumed 80% landfilling and 20% incineration.[16]

In the comparison of paper books to e-books, we assumed 1 tonne of wood can create 0.4 tonnes of books;[17] that the average mass of a book is 0.6 kg; and that 48 books of 360 pages are read during the lifetime of an e-reader with a battery whose charge lasts for 2-3 weeks. LCA data was sourced from Borggen *et al.*,[18] Moberg *et al.*,[19] and Borggen & Morberg.[20] For fate at end of life, we relied on EPA data[21] that indicated paper books are 43% recycled, 46% landfilled, and 11% incinerated and that eBooks are 48% recycled, 23% landfilled, and 29% incinerated. We assumed the half-life of a book in a landfill was 50 years.[22] In this comparison and that of corrugated boxes and envelopes, we used ecoinvent 3.9 for background data.

Sustainable Aviation Fuel

In the assessment of the process that creates sustainable aviation fuel (SAF) from wood fibre, we made the following assumptions that were informed by Ringsred *et al.*,[23] Yoo *et al.*,[24] and a report on SAF by the U.S. Department of Energy:[25] SAF is blended with jet fuel in a 50-50 ratio; the specific energy of SAF and that of traditional jet fuel is 43.2 MJ/kg; the carbon intensity of SAF is 25.9 g $CO_{2\ eq}$/MJ and that of jet fuel varies from 25.7 to 26.184.5 g $CO_{2\ eq}$/MJ (25.9 was used in this study); and that the GHG emissions from burning SAF and jet fuel are the same. Gasoline and diesel are co-products of the SAF production process, so we allocated impacts based on energy content.

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[15] Franklin Associates. (2011). *Life cycle inventory of foam polystyrene, paper-based, and PLA foodservice products*. Prepared for the Plastic Foodservice Packaging.

[16] U.S. Environmental Protection Agency. (2020). *Advancing Sustainable Materials Management: 2018 Tables and Figures*. Retrieved from https://www.epa.gov/sites/default/files/2021-01/documents/2018_tables_and_figures_dec_2020_fnl_508.pdf#page=43&zoom=100,77,85.

[17] Arjowiggins. (n.d.). *Saving wood*. Recycled Paper saves trees - Recycled Papers. Retrieved from https://recycled-papers.co.uk/green-matters/why-use-recycled-papers/saving-wood.

[18] Borggren, C., Moberg, Å., & Finnveden, G. (2011). Books from an environmental perspective—Part 1: Environmental impacts of paper books sold in traditional and internet bookshops. *The International Journal of Life Cycle Assessment, 16*(2), 138–147. https://doi.org/10.1007/s11367-011-0254-1.

[19] Moberg, Å., Borggren, C., & Finnveden, G. (2011). Books from an environmental perspective—Part 2: E-books as an alternative to paper books. *The International Journal of Life Cycle Assessment, 16*(3), 238–246. https://doi.org/10.1007/s11367-011-0255-0

[20] Borggren, C., & Moberg, Å. (2009). *Pappersbok och elektronisk bok på läsplatta—en jämförande miljöbedömning* (in Swedish, Appendices in English). Report from the KTH Centre for Sustainable Communications TRITA-SUS 2009:2. Stockholm. Available at http://www.sustainablecommunications.org/bok/

[21] US EPA (2020). Advancing Sustainable Materials Management: 2018 Tables and Figures Assessing Trends in Materials Generation and Management in the United States. https://www.epa.gov/sites/default/files/2021-01/documents/2018_tables_and_figures_dec_2020_fnl_508.pdf.

[22] *Ibid*.

[23] Ringsred, A., Van Dyk, S., & Saddler, J. (2021). Life-cycle analysis of drop-in fuel produced from British Columbia forest residues and wood pellets via fast pyrolysis. *Applied Energy, 287*, 116587. https://doi.org/10.1016/j.apenergy.2021.116587.

[24] Yoo, Eunji, Lee, Uisung, & Wang, Michael. *Life-Cycle Greenhouse Gas Emissions of Sustainable Aviation Fuel through a Net-Zero Carbon Biofuel Plant Design*. United States. https://doi.org/10.1021/acssuschemeng.2c00977.

[25] U.S. Department of Energy. (2023). *Sustainable aviation fuel – Review of technical pathways*. https://www.energy.gov/sites/default/files/2023/01/f43/sustainable-aviation-fuel-review-technical-pathways.pdf.

Biochar

Biochar is a soil amendment that can be used in place of compost. For this comparison, we relied on data from Puettmann *et al*.[26] and Siedt *et al*.[27] We used the average scenario from Puettmann and assumed a carbon : nitrogen : phosphorous : potassium (C:N:P:K) ratio of 116 : 3.2 : 1.1 : 2.8.

Oriented Strandboard (OSB) Used in Building Construction

We compared oriented strandboard (OSB) to fibre cement and MgO board using data from Puettmann *et al*.[28] and Soto[29] in the context of providing sheeting for a 15.6 m^3 house. We used a substitution ratio of 0.83 t OSB for 1.42 t fibre cement and a ratio of 0.83 t OBS for 1.10 t MgO board.[30] The production of OSB also creates 0.05 t of wood residue to which we allocated impacts based on mass. At end of life, we assumed OSB was 72.5% landfilled; 18.4% incinerated; and 9.1% recycled and assumed 100% of the fibre cement and MgO board was landfilled.[31]

Sawtimber and Cross-laminated Timber Used in Construction Applications

Our final comparisons were the use of sawtimber as a substitute for steel and for concrete in the manufacturing of a 10 m portal frame and the use of cross-laminated timber (CLT) in the construction of an office building. Unlike the wood fibre types used to make the products in the above comparisons, sawtimber and CLT are not feedstocks used for bioenergy. However, we included these analysis as a reference because of the documented carbon benefits of using sawtimber and CLT in place of steel and concrete.[32, 33] As wood, steel, and concrete are used in each of the frames whether it is wood-based, steel-based, or concrete based, the results are based on a net wood input (for instance, if the wood portal frame contains 2 kg of wood and the steel portal contains 0.5 kg of wood, only 1.5 kg of wood is considered. The quantity of wood, steel, and concrete in each of the portals is based on a study by Hegeir *et al*.,[34] and the data from modelling sawtimber was derived from a study from Milota.[35] Based

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[26] Puettmann, Maureen & Sahoo, Kamalakanta & Wilson, Kelpie & Oneil, Elaine. (2019). Life cycle assessment of biochar produced from forest residues using portable systems. *Journal of Cleaner Production.* 119564. https://doi.org/10.1016/j.jclepro.2019.119564.

[27] Siedt, M., Schäffer, A., Smith, K. E. C., Nabel, M., Roß-Nickoll, M., & van Dongen, J. T. (2021). Comparing straw, compost, and biochar regarding their suitability as agricultural soil amendments to affect soil structure, nutrient leaching, microbial communities, and the fate of pesticides. *Science of The Total Environment, 751*, 141607. https://doi.org/10.1016/j.scitotenv.2020.141607.

[28] Puettmann, M., Kaestner, D., & Taylor, A. (2020b). *CORRIM report: Life cycle assessment for the production of oriented strandboard*. Retrieved from https://corrim.org/wp-content/uploads/2020/12/CORRIM-AWC-OSB-Final.pdf

[29] Alonso Soto, A. M. (2021). *Life cycle assessment of magnesium oxide structural insulated panels* (Master's final degree project). Kaunas University of Technology, Institute of Environmental Engineering, Faculty of Mechanical Engineering and Design.

[30] Gorbunov, I. (2022). *Comparative life cycle assessment of a sustainable modular tiny-house* (Master's thesis). University of Twente, Civil Engineering. https://essay.utwente.nl/93535/1/Gorbunov-Ilya.pdf

[31] U.S. Environmental Protection Agency. (2020). *Advancing sustainable materials management: 2018 tables and figures assessing trends in materials generation and management in the United States*. https://www.epa.gov/sites/default/files/2021-01/documents/2018_tables_and_figures_dec_2020_fnl_508.pdf

[32] Leskinen, P., Cardellini, G., Gonzalez-Garcia, S., Hurmekoski, E., Sathre, R., Seppala, J., Smyth, C., Stern, T., & Verkerk, J. (2018). *Substitution effects of wood-based products in climate change mitigation* (From Science to Policy 7). European Forest Institute. https://efi.int/sites/default/files/files/publication-bank/2019/efi_fstp_7_2018.pdf

[33] Sathre, R., & O'Connor, J. (2010). Meta-analysis of greenhouse gas displacement factors of wood product substitution. *Environmental Science & Policy, 13*(2), 104-114. https://doi.org/10.1016/j.envsci.2009.12.005

[34] Hegeir, O. A., Kvande, T., Stamatopoulos, H., & Bohne, R. A. (2022). Comparative life cycle analysis of timber, steel, and reinforced concrete portal frames: A theoretical study on a Norwegian industrial building. *Buildings, 12*, 573. https://doi.org/10.3390/buildings12050573.

[35] Milota, M. 2020. Life Cycle Assessment for the Production of Southeastern Softwood Lumber. CORRIM. https://corrim.org/wp-content/uploads/2020/06/CORIRM-AWC-SE-Lumber.pdf

on these studies, we assumed 16.5 t of saw timber are needed to produce a 10 m portal frame that could replace a functionally equivalent frame produced using 7.7 t of steel and conducted the analysis based on the fraction of the portal frame that could be produced from the quantity of wood specified in the functional unit (i.e., 1 dry tonne wood comprises 4.5% of 10 m portal frame).[36] For the comparisons involving CLT, we assumed that 1 t of wood produces 0.76 t of CLT and that 782 t of CLT or 278 kg of steel is used in the construction of a 5-story office building.[37]

LCA Modeling

We modeled the carbon footprint of each wood fibre use and alternatives using both a static and dynamic approach. A static LCA accounts for all life cycle emissions until all degradable carbon has been remineralized and assumes all emissions occur in year 0. A dynamic LCA accounts for emissions in the year they occur and the warming these create until the end of a defined time period. One implication of dynamic LCAs is products that generate emissions over a period longer than the time bounds established for the study will be calculated as having net lower emissions than the same product analyzed using a static LCA. Dynamic LCA is applied only to bio-based products in an attempt to reflect the potential climate implications of first removing the carbon from the atmosphere and then keeping it outside the atmosphere from a significant period of time.

In all the models, we used secondary data from US Life Cycle Inventory (LCI) and ecoinvent v3.10 (unless v3.9 was noted above), employed the allocation cut-off by classification system model, and used SimaPro v9.6.0.1. Although the version of US LCI implemented in SimaPro is not the most current version, it was preferred over ecoinvent for fossil fuels because this prevented the need to make conversions from physical units to energy units. We calculated mass balances to validate the completeness of the data. Flow diagrams for use of wood fibre included in this case study are provided in the appendix.

Key Findings and Their Implications

For the pathways using from forest residues, BECCS (abated electricity production) generated more carbon benefits than bioenergy without CCS, biochar, plates, SAF, books, and corrugated containers with this pattern remaining consistent in both the static and dynamic LCAs (Figure 4). Bioenergy produced without CCS (unabated electricity production) provides greater benefits than all uses of pulp. Note that in this analysis, corrugated containers were compared to plastic envelopes in a worse-case scenario; however, in many cases corrugated containers will replace significantly more carbon-intensive materials.

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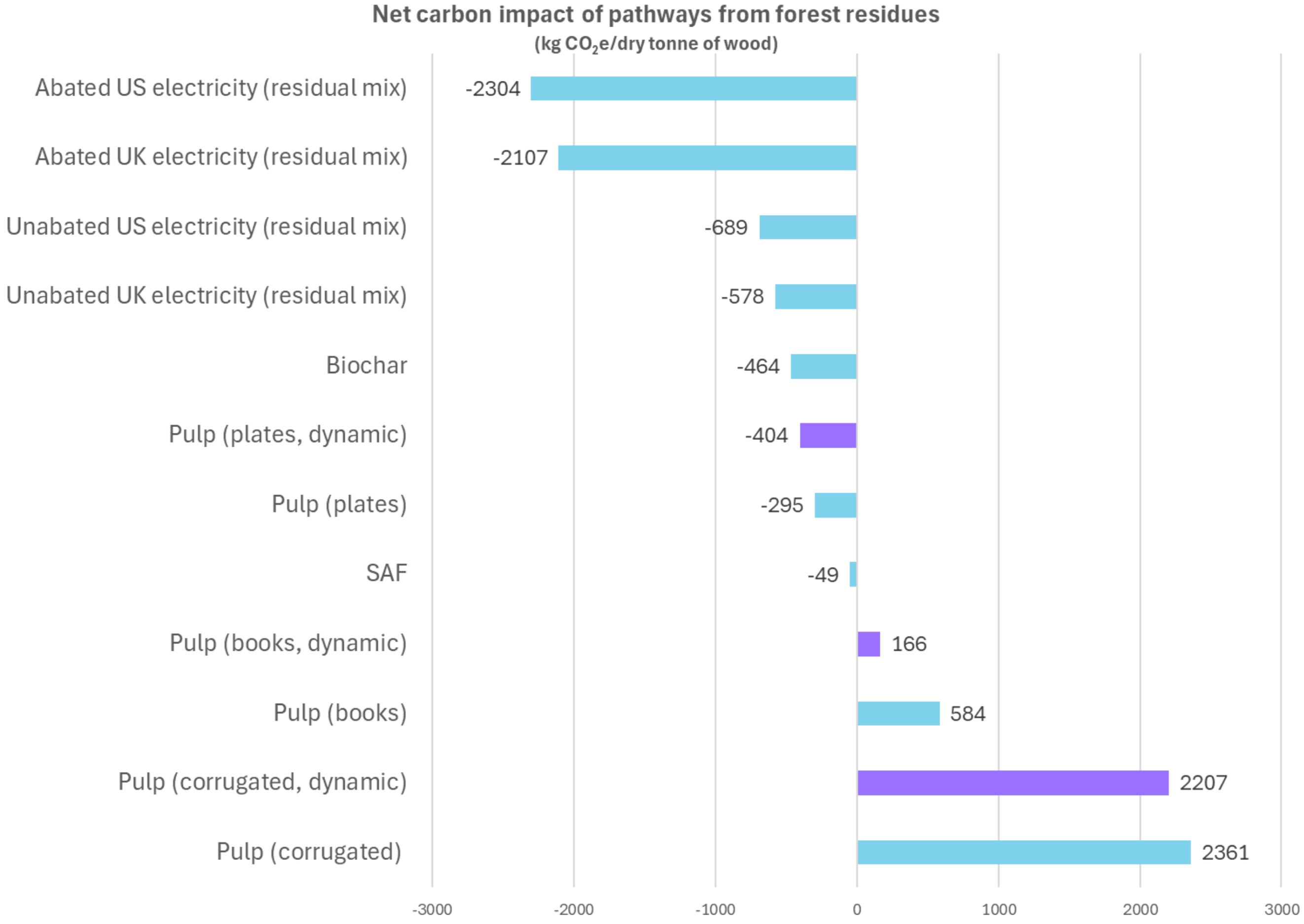
[36] Allan, Kevin, and Adam R. Phillips. 2021. "Comparative Cradle-to-Grave Life Cycle Assessment of Low and Mid-Rise Mass Timber Buildings with Equivalent Structural Steel Alternatives" *Sustainability* 13, no. 6: 3401. https://doi.org/10.3390/su13063401

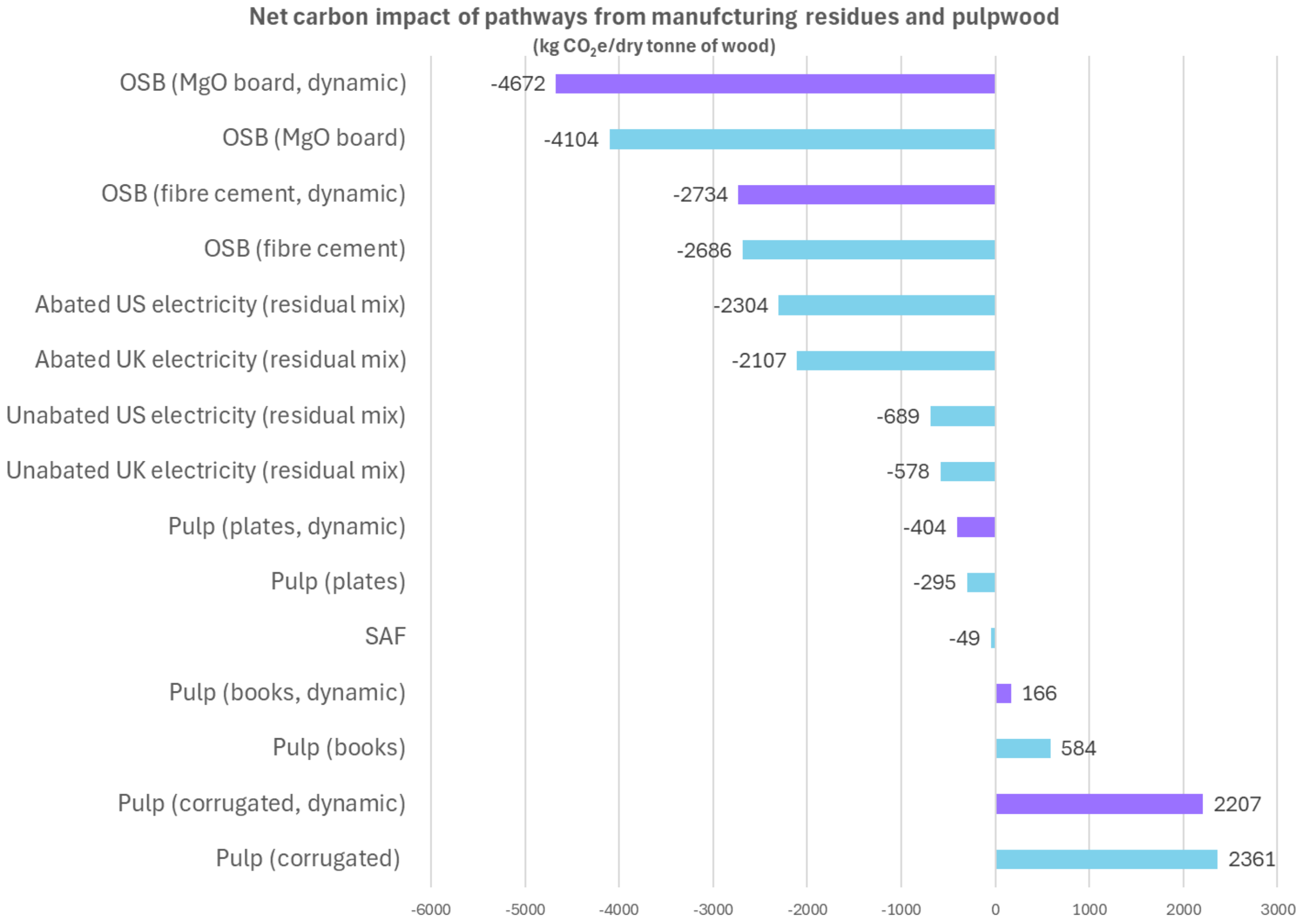
[37] Chen, Cindy X., Francesca Pierobon, and Indroneil Ganguly. 2019. "Life Cycle Assessment (LCA) of Cross-Laminated Timber (CLT) Produced in Western Washington: The Role of Logistics and Wood Species Mix" Sustainability 11, no. 5: 1278. https://doi.org/10.3390/su11051278

Figure 4: Carbon footprint results for pathways from forest residues



When manufacturing residues are used, only the carbon footprint of OSB as a substitute for MgO board or fibre cement as calculated in either the dynamic or static LCAs models generated a greater reduction in GWP than BECCS (Figure 5). As in the case of forest residues, the use of manufacturing residues for bioenergy even without CCS generates greater climate benefits than the other pathways (i.e., plates, SAF, books, and corrugated containers).

Figure 5: Carbon footprint results for pathways from manufacturing residues



Although sawtimber is not typically used to produce electricity and we do not intend these results to have implications for forest management, in this hypothetical scenario, BECCS generates a greater climate benefit than the use of sawtimber in construction applications (Figure 6). The greater climate benefit is a result of permanent storage of biogenic carbon in BECCS, the GHGs released during the production of steel and concrete that are part of the wood-based buildings, and—the end of life emissions from the sawtimber (Figure 7) although these latter emissions are very sensitive to assumptions about what percentage is landfilled.

In sum, these results provide evidence of the climate benefits of BECCS, particularly when using existing wood fibre feedstocks to produce electricity (Table 3). While, in general, wood products have lower carbon footprints than fossil-based alternatives, most alternatives also have a low carbon intensity, making the use of wood fibre products less advantageous from a climate perspective than their use for electricity. While the use of sawtimber for BECCS shows a greater climate benefit than other uses, other factors should be considered such as the risk of degrading carbon stocks, market pricing, and how sensitive the observed results are to assumptions about fate at end of life.

Figure 6: Carbon footprint results for pathways from sawtimber and CLT

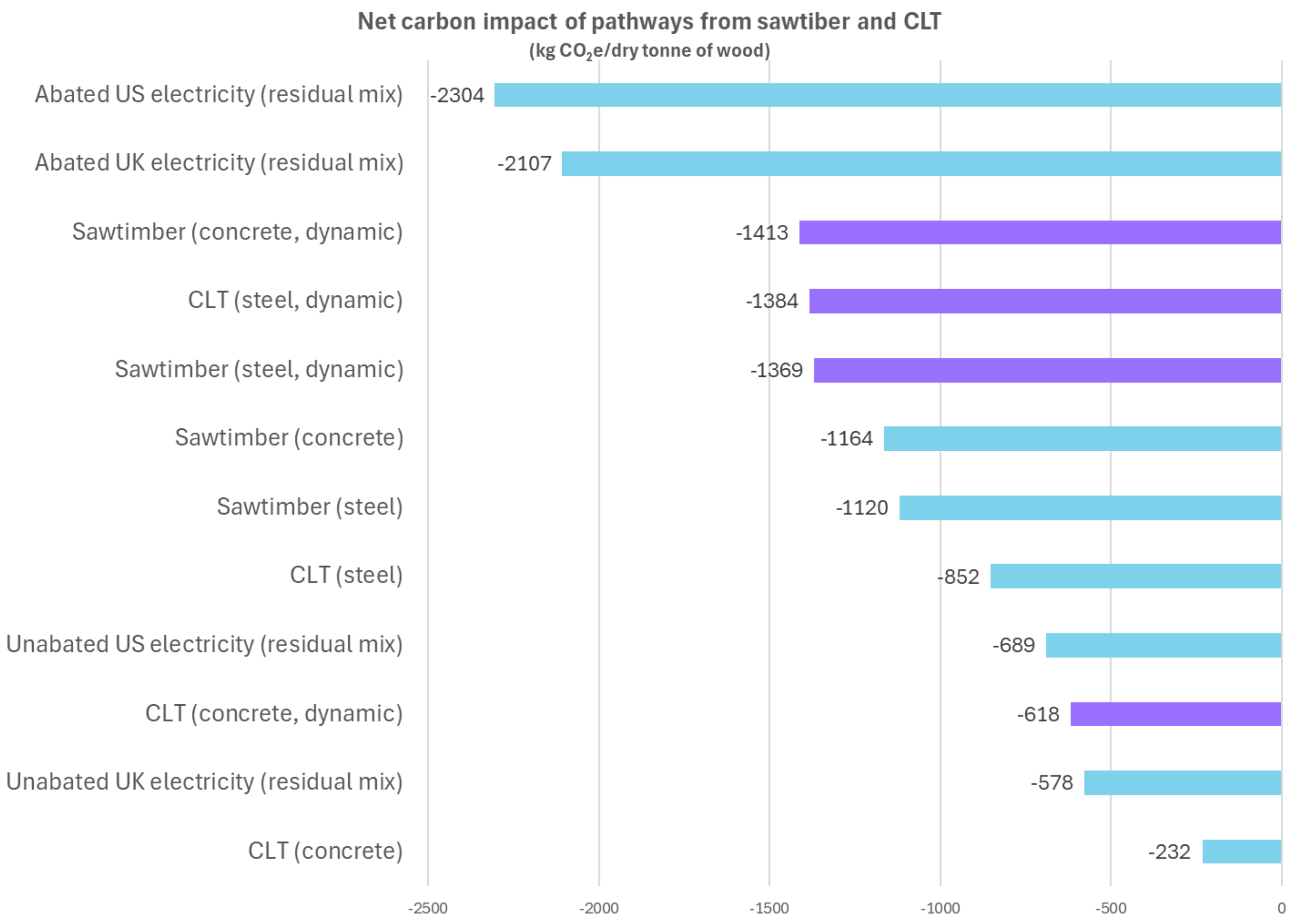


Figure 7: Discrete contributions to the carbon footprint of sawtimber used in a construction application

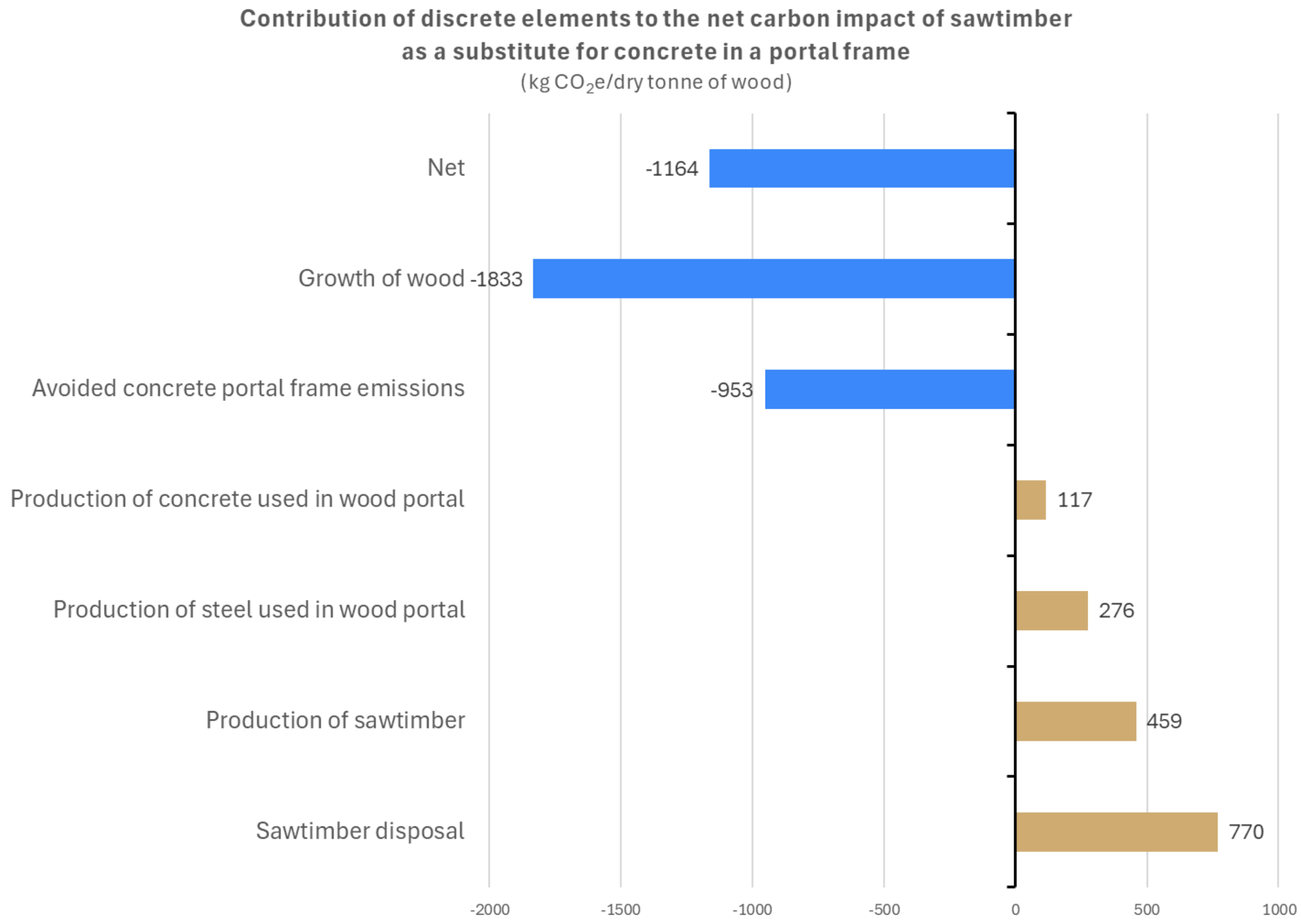


Table 3: Summary of net climate impacts

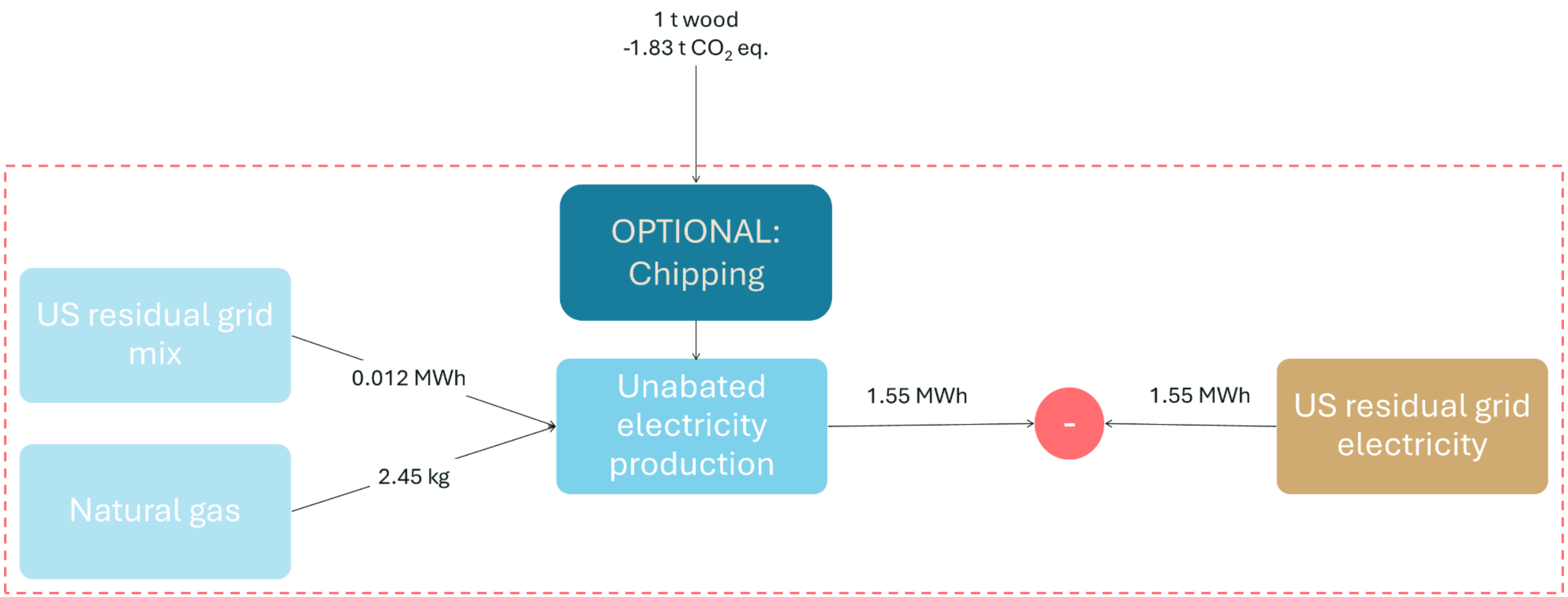
Wood fibre use	Non-wood-based alternative	Net kg $CO_{2\ eq}$/FU (including biogenic CO_2 emissions and uptake)	
		Static	Dynamic
OSB sheathing	MgO board	-4,104	-4,672
OSB sheathing	Fibre cement	-2,686	-2,734
Abated US electricity (chips)	Residual US electricity	-2,304	No effect
Abated UK electricity (pellets)	Residual UK electricity	-2,107	No effect
Unabated US electricity (chips)	Residual US electricity	-689	No effect
Unabated UK electricity (pellets)	Residual UK electricity	-578	No effect
Biochar	Compost (C,N, P & K)	-464	No effect
Pulp – Plates	Polystyrene Plates	-295	-404
Sustainable aviation fuel (SAF)	Jet fuel	-48.6	No effect
Pulp – Books	E-book	584	166
Pulp – Corrugated containers	LDPE envelopes	2,361	2,207
Sawtimber portal frame	Concrete	-1,164	-1,413
Sawtimber portal frame	Steel	-1,120	-1,369
Cross-laminated timber (CLT) in 5-story building	Steel	-852	-1,384
Cross-laminated timber (CLT) in mid-rise building	Concrete	-232	-618

Appendix: Flow Diagrams for the Wood Uses Studied

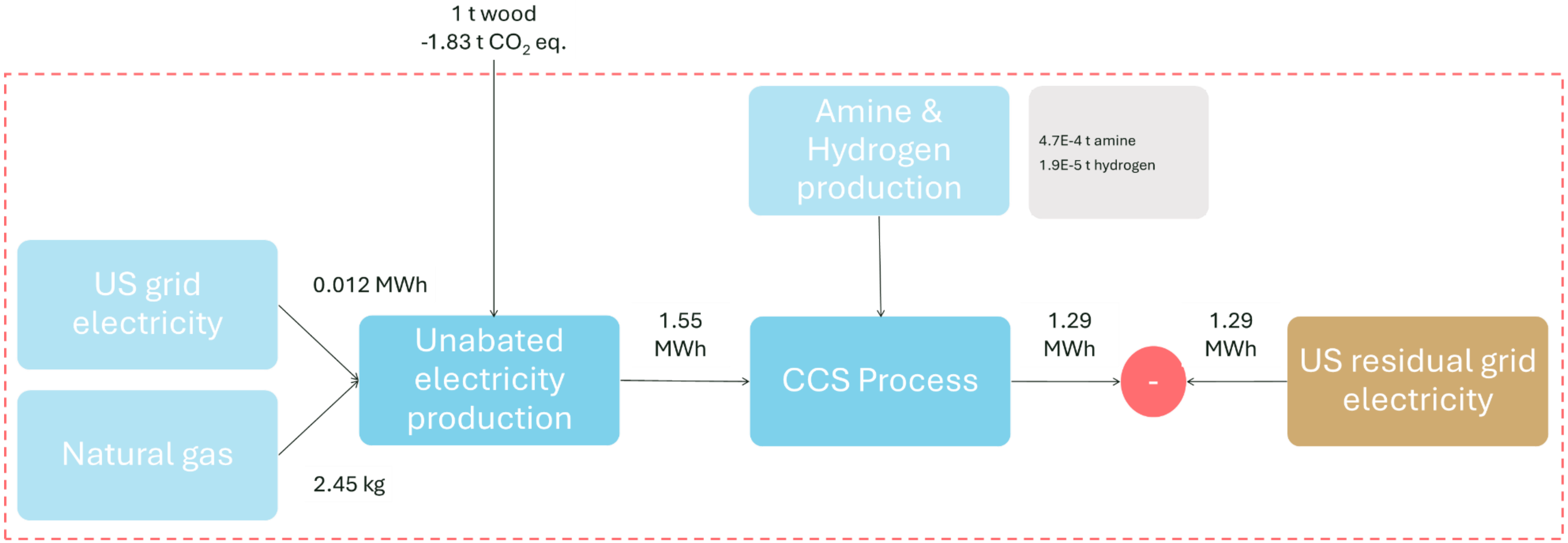
In the following pages, details are provided about each use of wood fibre included in the case study. In all the diagrams, $CO_{2\ eq}$ includes biogenic CO_2 emissions but not removals based on the rationale is that removals are the same in all pathways and this study aims at assessing different paths for the biogenic carbon in addition to life cycle fossil fuel GHGs. All tons (t) are dry metric tonnes, and the following legend applies to all system diagrams:

- Wood product system - foreground
- Wood product system - background
- Counterfactual- foreground
- Counterfactual- background
- System boundaries

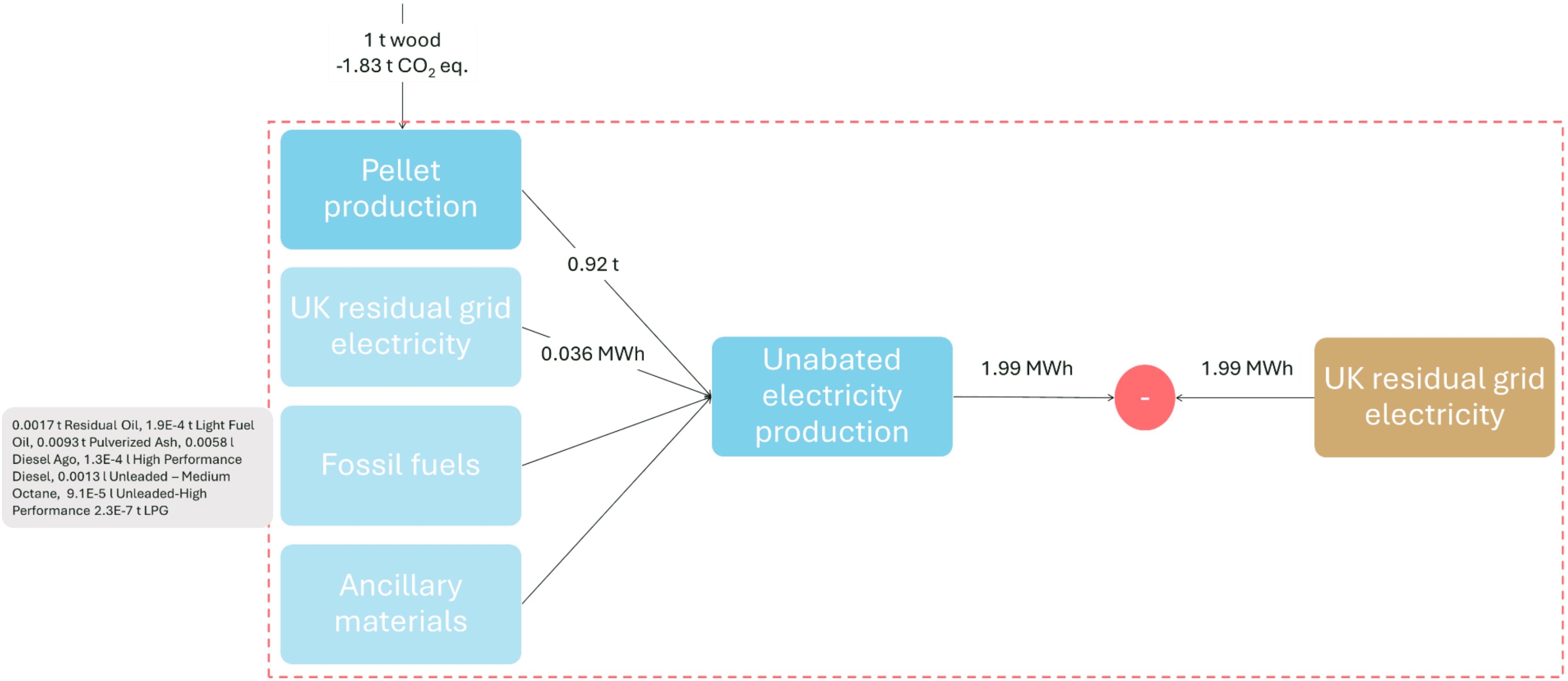
1. Electricity in the US (from Chips, w/o BECCS) Compared to US Residual Grid Electricity



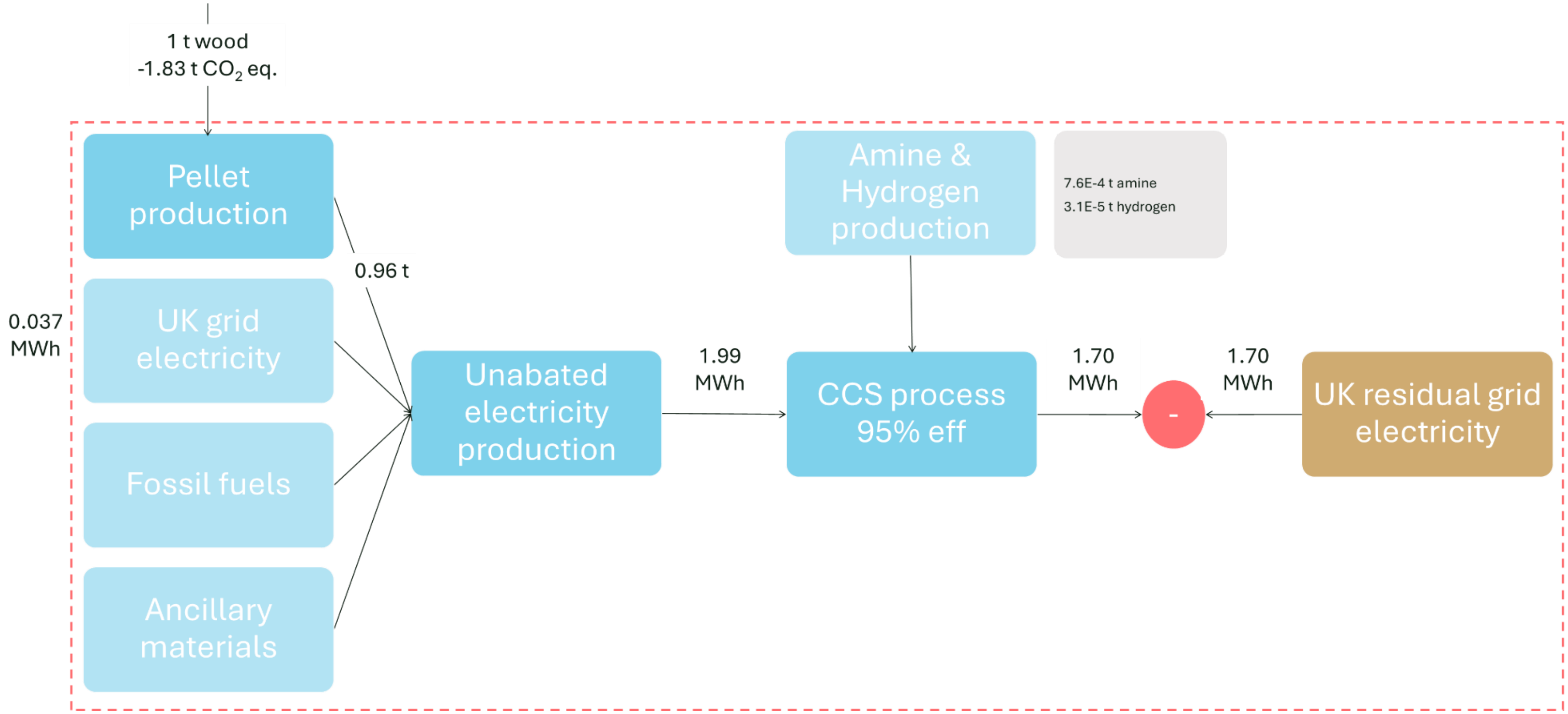
2. Electricity in the US from Chips, w/ BECCS Compared to US Residual Grid Electricity



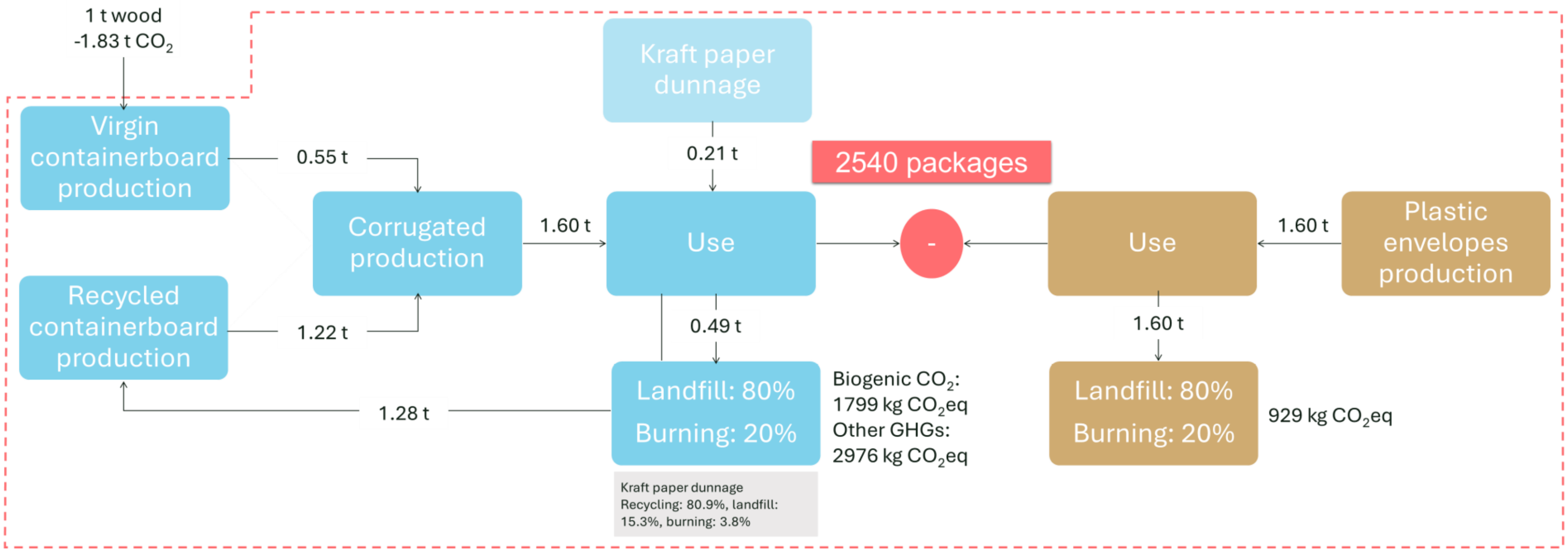
3. Electricity Production in the UK from Pellets w/o BECCS Compared to UK Residual Grid Electricity



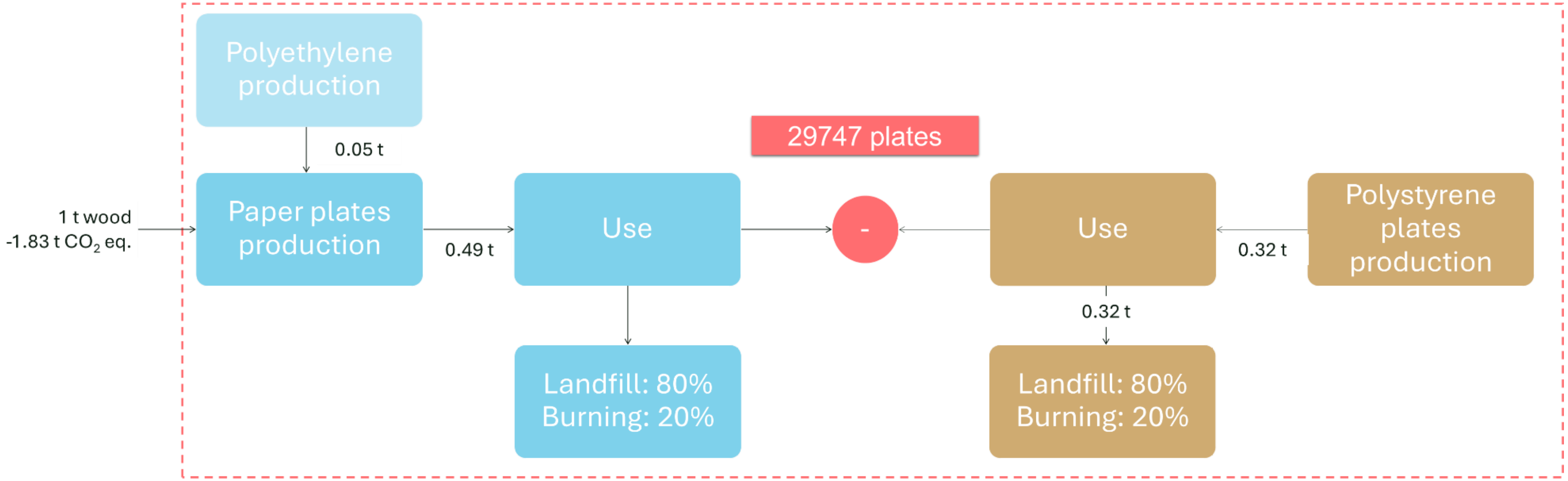
4. Electricity Production in the UK from Pellets w/ CCS Compared to UK Residual Grid Electricity



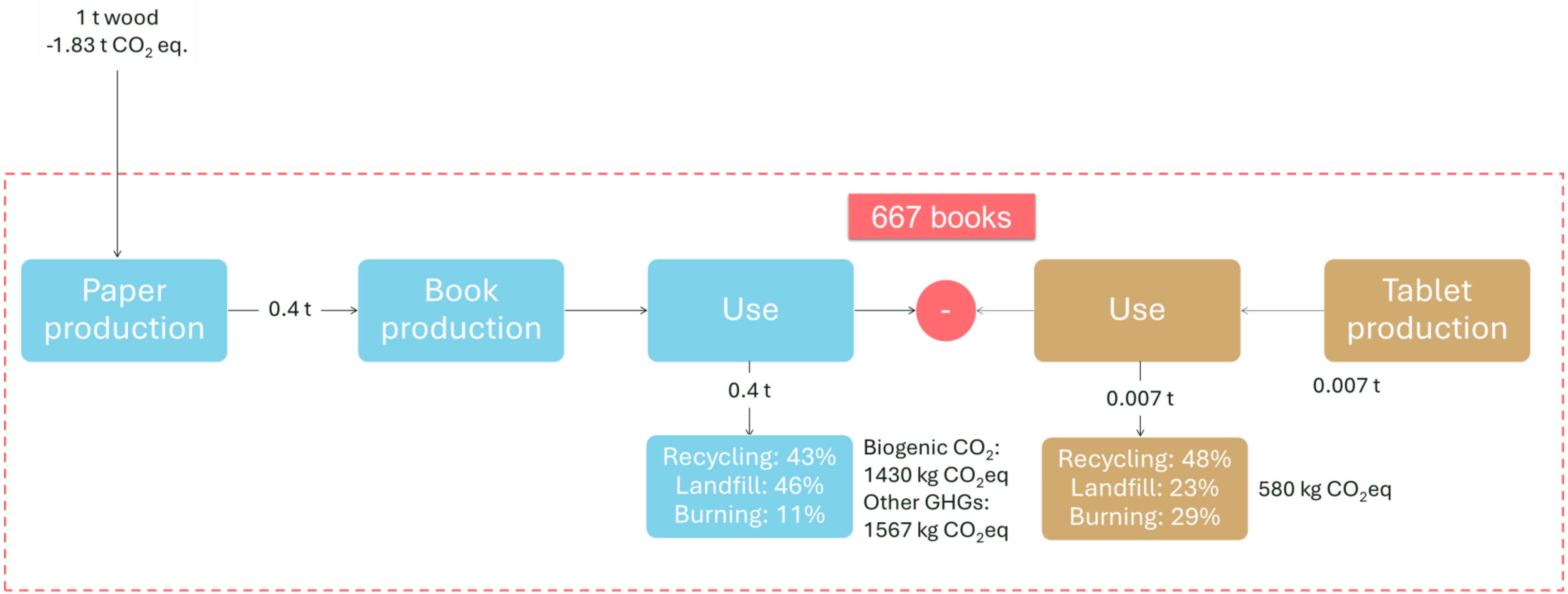
5. Corrugated Boxes Compared to Plastic Envelopes



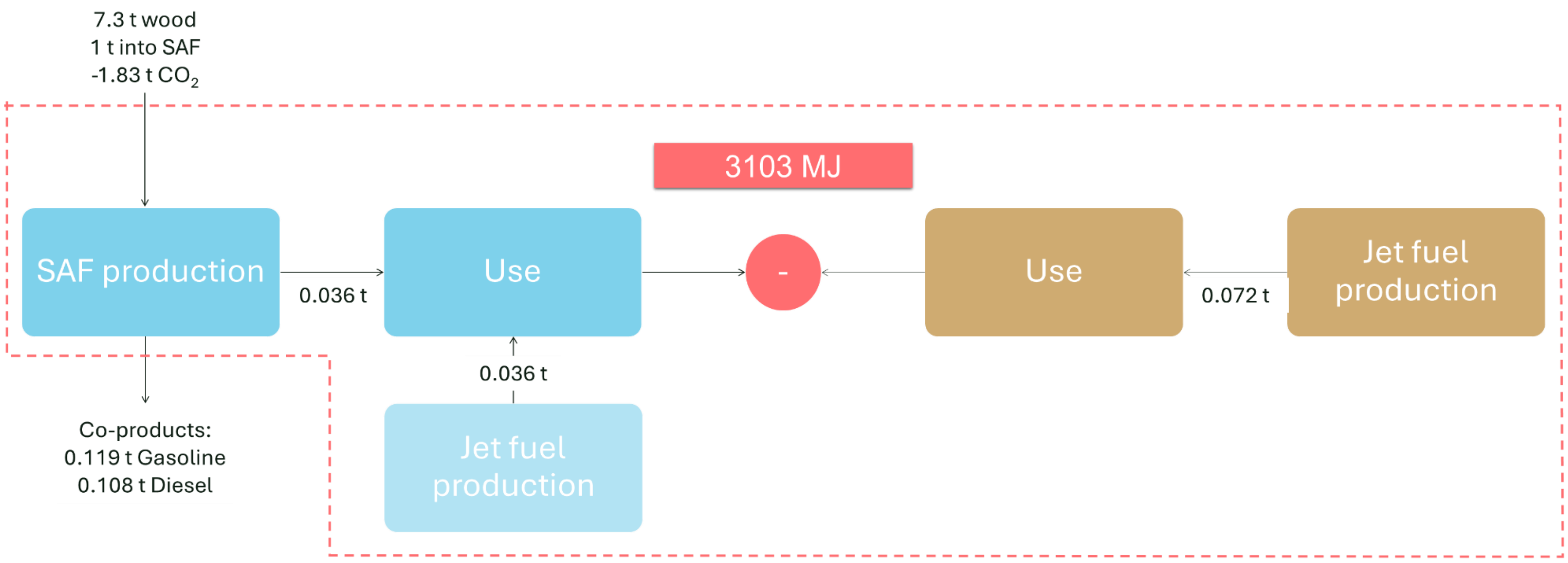
6. Paper Plates (PE-Coated Paperboard) Compared to Polystyrene Plates



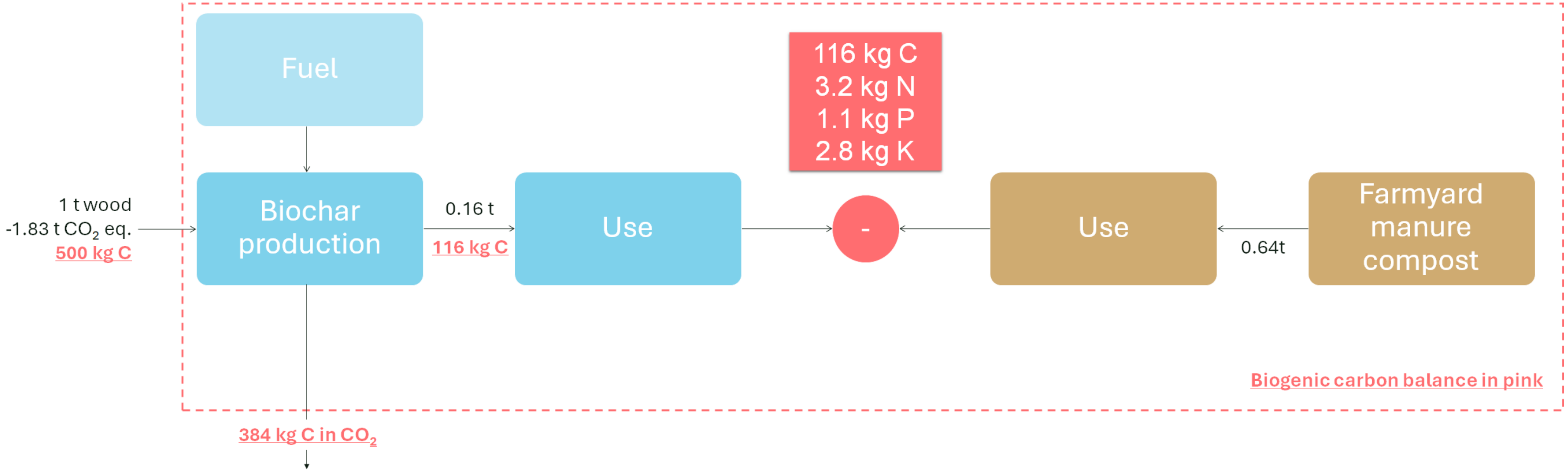
7. Paper Book Compared to e-Books



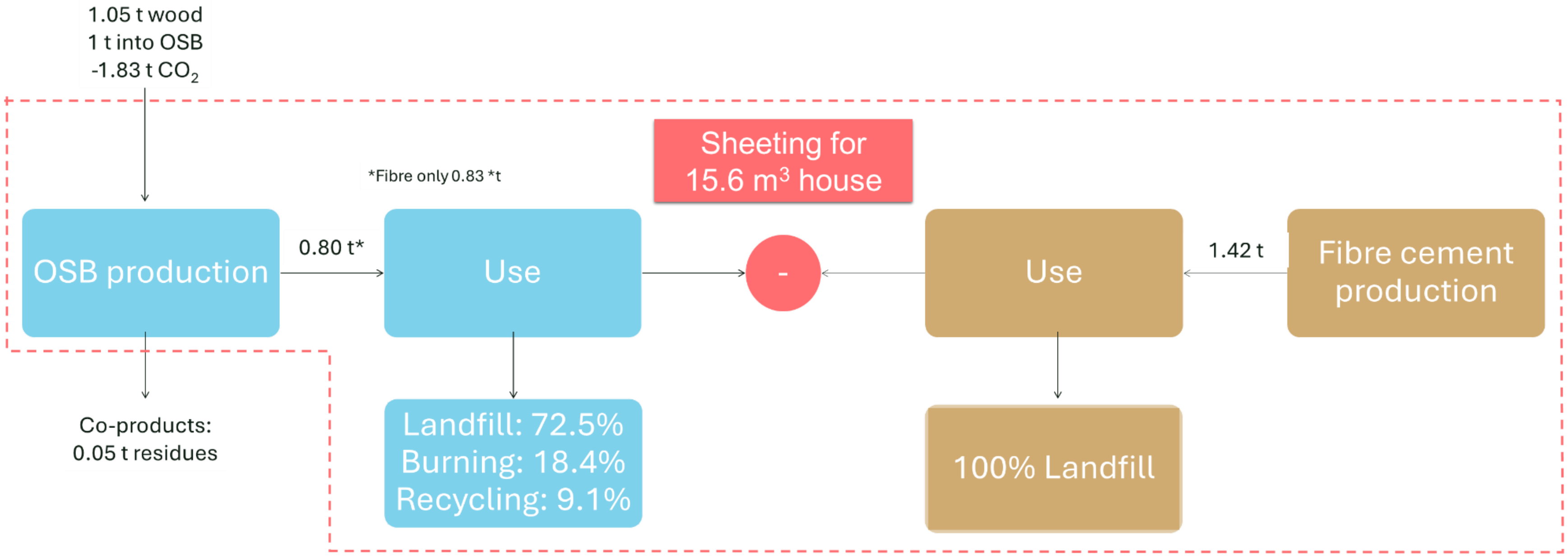
8. Sustainable Aviation Fuel (SAF) Compared to Jet Fuel



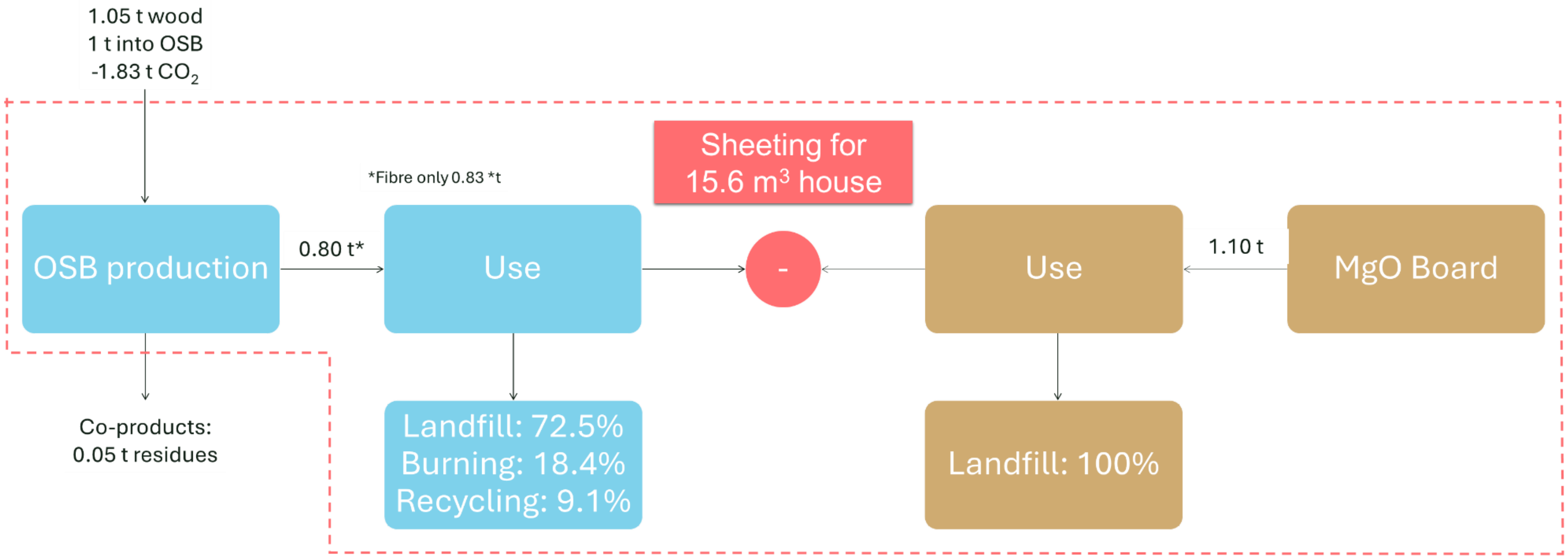
9. Biochar Compared to Farmyard Manure Compost



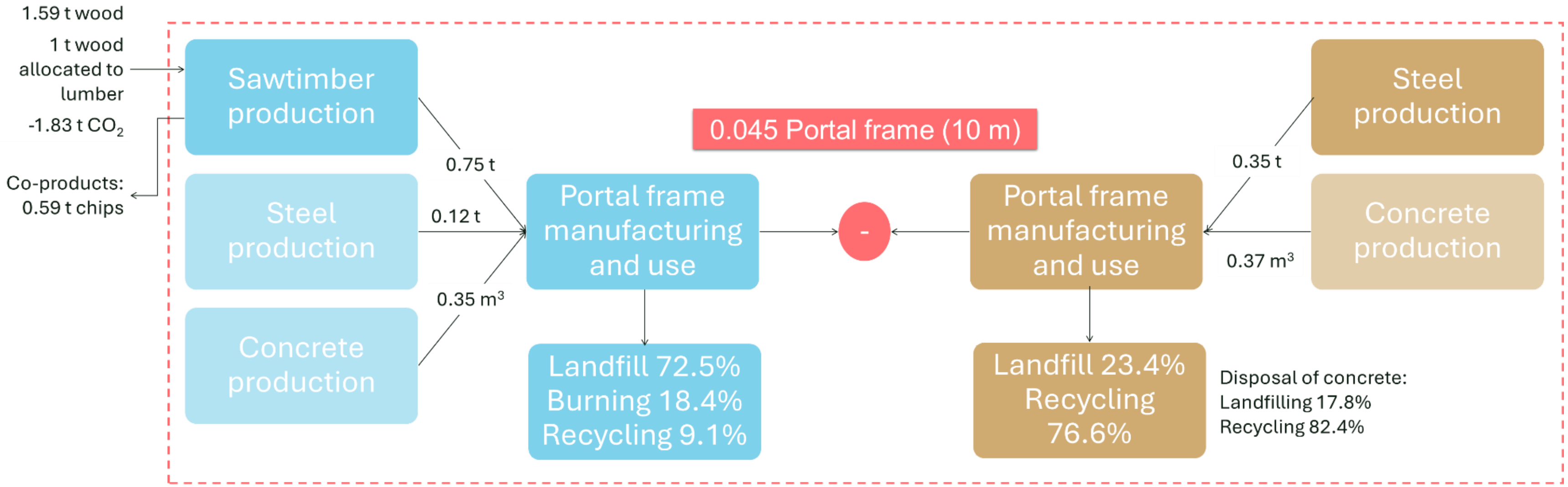
10. Oriented Strandboard (OSB) Compared to Fibre Cement



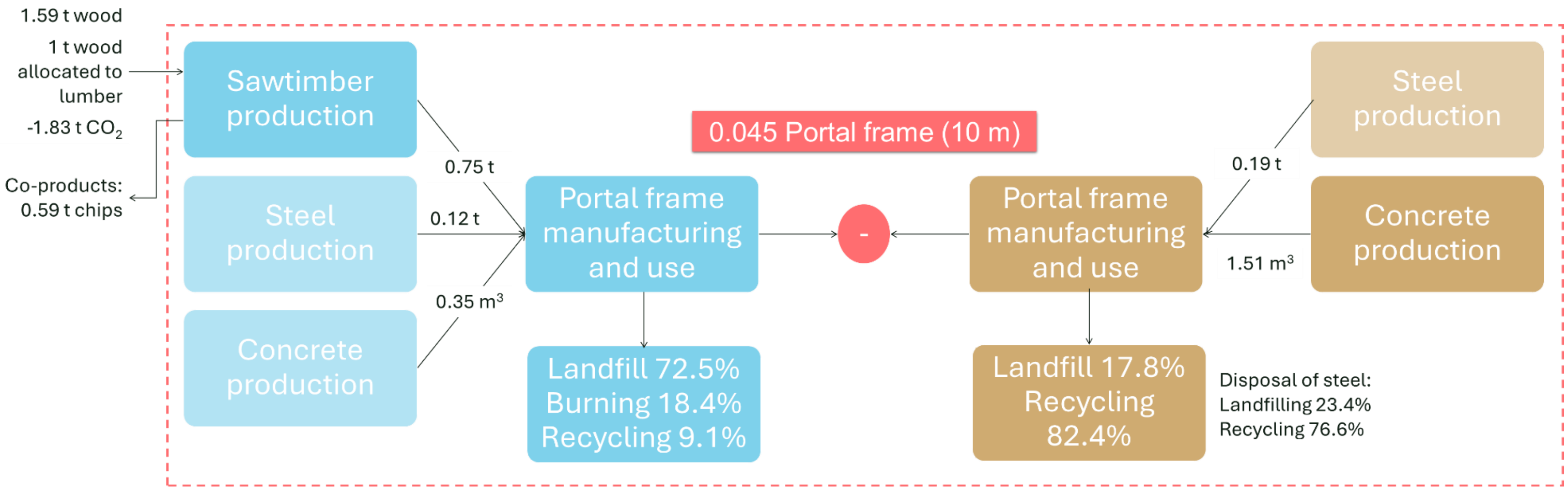
11. Oriented Strandboard (OSB) Compared to MGO Board



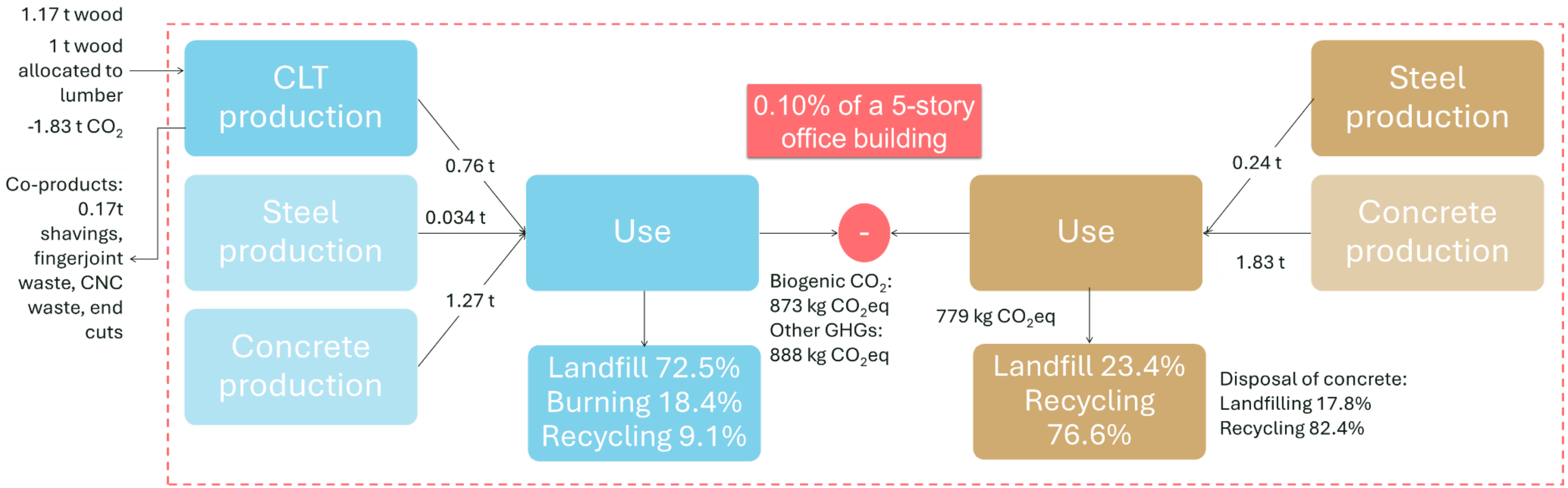
12. Sawtimber Compared to Steel



13. Sawtimber Compared to Concrete



14. CLT Compared to Steel



15. CLT Compared to Concrete