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BUILDING TOWARD ZERO EMBODIED CARBON

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ABSTRACT: This paper reviews the factors that determine the contribution of timber buildings to CO_2 emissions abatement, and how they are likely to impact our transition to net zero. Factors include projected volume demands of future building construction; building embodied carbon vs operational carbon; the carbon emissions of different construction materials; the growth and benefits of prefabrication; forests as carbon sinks under sustainable harvesting regimes and the impact of COP26; building end-of-life choices, and political drivers for the increased use of timber for carbon sequestration.

KEYWORDS: embedded, carbon, sequestration, end-of-life

1 INTRODUCTION

With global building floor area expected to double by 2050 [1], demand for raw materials is likely to grow proportionally. Embodied carbon emission from so much new construction will grow similarly unless we act to mitigate its effect.

The contribution of buildings to our global carbon emissions is typically estimated in the range 30-40% [2,3,4]. As a portion of those building emissions, embodied carbon emissions from building construction are typically estimated in the range 10-30% [5]. As efforts to reduce building operational carbon emissions begin to take effect, embodied emissions will continue to increase as a percentage of total building emissions. So the balance of mitigation effort will need to shift - attenuating building embodied carbon will play an increasingly important part in helping achieve net zero carbon by 2050, the goal that is consistent with efforts to limit the long-term increase in average global temperature to 1.5 degC [6].

The cement and steel industries are well aware of the challenge and are ramping up efforts to respond. Meanwhile, timber construction appears to offer an attractive alternative to concrete and steel in climate terms. Depending on availability of sustainably managed forest resource and end-of-building-life strategies, it can provide sequestration of biogenic carbon, or displacement of fossil fuel from current energy generation. For timber to fulfil its potential, government policy regarding the abatement of carbon emissions will be key, at international, national, and local levels. These and other factors affecting timber's likely contribution to climate change mitigation are discussed below.

2 OPERATIONAL VS EMBODIED EFFECTS

Building embodied energy (EE) is the energy consumed during production of a building, ie energy expended in extraction, conversion and transportation of raw materials, and in their processing and manufacture as building components. In terms of EN 15978 boundaries [7], it can be extended across modules A1-A3 ('cradle to gate'), or A1-A5 ('cradle to site') if the building's construction phase is to be included. Embodied carbon (EC) refers to the carbon emissions associated with the embodied energy, plus other emissions associated with the creation of materials, such as calcination in the case of cement, reduction in the case of iron, and photosynthesis in the case of timber.

Operational energy (OE) is the energy consumed in using the building over its lifespan, including heating, cooling, ventilating, lighting, appliances and equipment. Operational carbon (OC) refers to carbon emissions associated with the operational energy, typically deriving from electricity generation or on-site fossil fuel combustion.

Studies vary widely in their assessment of the relative portions of EE (or EC) and OE (or OC) in buildings. At the high end, for an energy efficient apartment block in Sweden with a projected lifespan of 50 years, EE accounted for 45% of total energy [8], with recycling potential estimated at 35-45% of EE. A more modest estimate puts EE at 'usually not more than 30%' [9]. One of the most extensive studies [10] covering 73 sample buildings across 13 countries estimated average EE at 10-20% of total life cycle energy, though changes to the EE/OE balance since publication (2010) would likely have seen that range increase.

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Regarding changes to these ratios over time, two effects are at play. Firstly, thanks to the historically greater emphasis on reducing operational energy through more energy-efficient heating and cooling systems, improved building insulation, take-up of 'passive' design strategies, changing user behaviours, regulation, and voluntary ratings schemes, OE continues to reduce, so increasing the EE/OE ratio.

Secondly, the transition to renewable energy has acted to reduce the carbon intensity of OE, whereas much of the carbon emission associated with material production, particularly of cement and steel, is not reducible in a similar way, being inherent in the chemical processes underlying the material's production. So the EC/OC ratio is rising faster than the EE/OE ratio, placing more urgency on attenuation of EC if the construction industry is to play its part in reducing global emissions.

3. CONSTRUCTION MATERIALS

The raw materials we extract from the earth and turn into products for building construction contribute significantly to our annual global greenhouse emissions. Concrete and steel currently dominate the choice of construction materials. Both are the subject of substantial R&D investment to reduce their carbon footprints, but reductions are constrained by the fact that conventional production of both materials involves chemical processes that necessarily off-gas CO2 as a by-product.

Cement is typically cited as contributing around 8% of global carbon emissions [11]. Combustion of fuel for kiln heating accounts for around 40% of that, and calcination of limestone around 60% [12]. Calcination is intrinsic to the production of normal Portland cement, and not amenable to reduction.

Cement substitutes hold much promise, with blast furnace slag, fly ash, and silica fume among the most commonly used. Their use in meaningful proportions raises issues for designers and contractors however in terms of lower early strength. This can translate into longer production cycle times for precast components, longer floor-to-floor cycle times for in-situ construction with delayed de-propping of formwork, and delays in application of prestressing for post-tensioned floors and beams.

Recycling of concrete still offers much scope for implementation [13]. It includes recycling into aggregate for road construction or backfilling, recycling into aggregate for new concrete production, and re-use of precast elements, all of which see more take-up in countries with policies constraining landfill dumping.

The steel industry has made big strides in improving energy efficiency but still accounts for around 8% of global emissions [14]. As with cement, emissions from conventional steel production include an irreducible component inherent in the chemical pathway – reduction of iron oxides generating CO2. Some progress has been made experimenting with alternative reduction environments, including the use of hydrogen [15]. Most promising in the short term however may be increasing the extent of recycling, where studies show plenty of room for improvement globally [16,17].

With the challenges faced by cement and steel in transitioning to low carbon production, construction in timber, or timber composites with concrete or steel, presents itself as an attractive third option.

4. EMBODIED CARBON AND PREFABRICATION

Leaving aside the potential benefits from biogenic carbon storage in wood, embodied carbon to produce a building in timber is typically less than a similar building in concrete or steel [47,48]. Production in timber is typically less energy intensive, typically uses renewable fuel, doesn't involve chemical processes that off-gas CO2, and is well-suited to prefabrication.

Fig. 1. The timber in this prefabricated office building for Sky UK represents -1442 t biogenic CO2, ie sequestered from atmosphere. Emissions from manufacture and transport from Austria represented +200 t, leaving embodied CO2 of -1242 t (Module A1-A5 including biogenic). The alternative structure with steel frame and concrete slabs would have cost +553 t embodied CO2 (A1-A5), ie emitted to atmosphere [44]. Given the building's energy saving features like rooftop PV, LED lighting and CCHP, the -1242 t CO2 represents about 13 years of operational emissions. Even if the sequestered carbon is returned to atmosphere at end-of-life, the 353 t benefit (553 t – 200 t) cf the steel/concrete composite alternative, remains. Photo copyright Simon Kennedy.

Prefabrication can reduce the embodied carbon footprint of a manufactured item by concentrating material resources and equipment at a single location, so reducing the transport costs of diverse materials to distributed construction sites, by encouraging optimisation of material usage and minimisation of waste, and by creating more opportunity for recycling. Precast concrete components for example benefit from indefinite reuse of

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steel forms compared to more limited reuse of timber formwork typical of in-situ concrete construction.

Because of its easy machinability, timber is particularly well-suited to prefabrication, and this typically leads to local generation of a valuable biomass energy resource during milling and machining. It is common now for manufacturers of glulam, CLT and LVL to operate plants at or near energy self-sufficiency, with a very small carbon footprint. This is achieved by harnessing all residuals for heat/energy generation – harvesting and sawmilling residuals including bark, and offcuts and sawdust from manufacturing.

At its Varkaus LVL mill for example, Stora Enso operates combined heat and power plants using bio- and recycled fuels and is energy self-sufficient (self-reported [18]). Wiehag's glulam plant at Altheim near Stuttgart generates 38 GWh pa of renewable energy by biomass conversion from 10,000t pa of offcuts and sawdust. This is enough to supply all of the plant's electricity and heating needs, including space heating and kiln drying. Excess offcuts are sold as product and excess power is sold to the grid (self-reported [19]). At Nelson Pine's LVL plant in New Zealand, over 70% of energy requirements are for kiln heating, and are almost entirely accounted for by burning of wood residues from sustainably managed forests (self-reported [20]). According to a Canadian study, two-thirds of the country's total energy consumed in converting logs to dry-dressed lumber is attributable to drying operations, and on average 50% of energy use is derived from renewable biomass fuel [21].

Fig. 2. Wiehag's glulam plant at Altheim near Stuttgart. Photo: Wiehag

5. FORESTS AS CARBON SINKS

For current timber markets to expand, the supply of wood from sustainably managed forests also needs to expand. According to the IPCC, increasing the global resource of sustainably managed forests represents a benefit for global draw-down of CO2 : 'In the long term, a sustainable forest management strategy aimed at maintaining or increasing forest carbon stocks, while producing an annual sustained yield of timber, fibre or energy from the forest, will generate the largest sustained mitigation benefit" [22]. Regarding establishment of new plantation forests, they will be subject to competing land use claims, some of which can also point to carbon benefits, such as planting for biofuel crops. Supply of construction round wood from existing plantations is already subject to competition from biomass energy feedstock markets, which also claim carbon benefits, through fossil fuel substitution. More rigorous life-cycle assessment (LCA) will be an important tool in adjudicating between these competing claims in terms of climate change mitigation potential.

Despite competition for land, Europe's forests have increased in area by 9% over the past 30 years [23], to over a third of the continent's land surface. The associated biomass and stored carbon have grown by 50%, with only three quarters of the net annual wood increment harvested [24], so creating a net carbon draw-down benefit.

Fig. 3. Sweden's plan is to achieve net zero carbon by 2045, with forest carbon storage an important part of the plan. Forest stock has doubled in the past 100 years [45], with harvest rarely exceeding growth in any year. In 2018, CO2 drawdown to forests accounted for 80% of Sweden's 52mt CO2-e emissions [46].

Round wood harvesting in Europe benefits from a long tradition of sustainable forest management. Well-regulated extraction practices have earned European forestry its social licence. The same is not true in other temperate regions however, such as Australia, where harvesting in native forests remains controversial and politically sensitive. Foresters refer to the 'abattoir syndrome', where we enjoy timber products but prefer not to see a tree cut down. That is despite studies favouring managed forests over conservation forests for CO2 draw-down potential [43]. Increasing take-up of forest management certification should help alleviate these concerns. Globally, cumulative forest area managed under the major certification schemes has increased over 30-fold since 2000 [25], to around 30% of worldwide round wood production [26].

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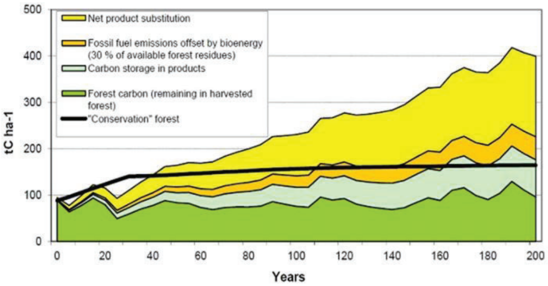

Fig. 4. Native forests in the state of New South Wales, Australia, include 'conservation' forests, with no harvesting, and 'multiple use' forests, with sustainable harvesting. The potential carbon drawdown of each forest type was modelled over a 200 year period. The conservation forest quickly reaches carbon equilibrium (heavy line), as does the multiple use forest. Allowing for potential product substitution benefit and fossil fuel offset benefit from biomass energy conversion of forest residues, the multiple use forest continues to extract carbon from atmosphere (top line) [43].

Deforestation in tropical regions casts a shadow over the timber industry's claims to be contributing to climate change mitigation however. Government responses in temperate regions have included regulation to control importation of illicit product, often with criminal convictions applying. Funding programmes such as UN REDD, the Norwegian Climate and Forest Initiative, the Amazon Fund, and the Billion Tree Campaign have had some effect, and there are now instances of deforestation reversal. Deforestation reached its peak in Costa Rica in the 1980's and has since reversed thanks to legal controls on land use change and stable funding through a PES (payment for ecosystem services) scheme [27]. ITMO's (internationally transferred mitigation outcomes) agreed at COP26 may open the way for funding flows into regions most affected (see 'Political Drivers' below). In the private sector, consumer goods retailers and manufacturers with a combined market value of USD2tr and financial institutions managing USD9tr recently pledged to eliminate deforestation from their supply chains and portfolios [28].

6. END-OF-LIFE CHOICES

LCA allows us to quantify embodied carbon in products and so to encourage behaviours that will move us closer to the circular economy. The challenge with buildings as products is predicting their full life cycle, particularly end-of-life (EOL) scenarios that may occur fifty years or more from construction. That is ambitious if not fanciful, but necessary for the equitable allocation of life-cycle carbon emissions, through fuller application of the LCA toolbox.

Regarding the life cycle of timber buildings, potential EOL scenarios are :

1. *Reuse.* Complete timber components are salvaged for reuse in a future building. Carbon already stored in the timber continues to be stored. Reuse will become more attractive with the increasing use of large section glulam or LVL beams and columns and large CLT floor and wall panels. Elements like these have had enough value added during manufacture to warrant reuse even in the present-day market. A way of quantifying the carbon benefits or disbenefits of reuse is to measure potential outcomes according to Module D of EN 15978 [29], which considers carbon emissions beyond Stage C, End-of-Life. The benefit of reuse is considered to be the emissions difference between reuse of timber components in a hypothetical future building versus the emissions associated with producing a functionally equivalent building using standard practices and market averages.

EOL scenarios are usually uncertain, as are Module D impacts. The benefit of reporting them, even if only qualitatively, is that they offer a measure of 'circularity' of a building project, or its ability to contribute to the low carbon circular economy, which will be key to hastening the decarbonisation of the construction industry. An example is design for deconstruction, which attracts credit in Module D when advantage is taken of reuse.

2. *Recycling*. In this scenario timber is chipped or shredded and repurposed for a variety of potential uses, including OSB or particleboard manufacture, and agricultural uses such as organic mulch for soil nutrition, ground cover for moisture retention and weed suppression, or animal bedding. Depending on the jurisdiction, preservative treated, glued, painted or coated wood may be banned or restricted for some recycling uses.

In LCA terms, recycling of demolition timber into chips for some new use is reported as a C3 transfer of stored carbon to the new product in the same way as for reuse. There are likely however to be additional fossil carbon emissions due to the EOL processing, which is necessary before the new recycled product can be created.

3. *Energy Recovery*. Timber is burned in an energy recovery facility, so the stored CO2 returns to atmosphere, along with small quantities of other greenhouse gases. Applying the EN 15897 Module D approach to the LCA of a timber building where energy recovery is assumed at EOL produces a carbon benefit equal to the difference between the carbon cost of BAU (business as usual) energy production and the carbon neutral cost of the energy retrieved from the timber, assuming of course the equivalent timber is regrown.

Whether the regrowth timber is assumed to have sequestered its carbon before the incineration event or after, raises the question of timelines for biogenic carbon.

'Dynamic LCA' models have been developed to try to account for the relative timings of capture and release of biogenic carbon [30], though they are limited in use by the quality of data available regarding carbon flux in managed forests.

The other uncertainty regarding the calculation of energy recovery from the burning of wood is estimating the Module D benefit in terms of substitution of this carbon-neutral energy for BAU energy. Logically, BAU should refer to conditions likely to prevail at actual EOL, when the substitution occurs. In countries where electricity generation is currently carbon heavy, the future substitution benefit from biomass renewables is likely to be less than currently, assuming progress is made in decarbonising the electricity mix. On the other hand, in countries where hydropower is currently dominant, the substitution benefit would be small both currently and in the future. Less conservative interpretations of Module D calculate BAU energy based on current not future conditions, on the grounds EN 15804:2012 (Sustainability of Construction Works – EPDs) 6.4.3.3 permits this assumption.

Of course when the local grid has converted entirely to renewables, there will be no substitution benefit at all. If CCS (carbon capture and storage) has progressed to commercial feasibility by then, it will open up an alternative means of permanently sequestering the biogenic carbon, by capture and burial of carbon from the flue gases.

Biomass energy conversion raises questions of air pollution, both particulate and gaseous. While incineration of virgin wood is commonly permitted, burning of preservative treated, glued, painted or coated wood is commonly banned or restricted. Scrubbers can neutralise acids in the emission stream; fabric filters and electrostatic precipitators can remove particulates, and higher furnace temperatures can break down combustion chemicals into simpler less harmful compounds, but optimal application of these technologies comes at a price and is far from universal [31].

4. *Storage in Landfill.* While dispatch of EOL timber to landfill is prohibited in some countries and restricted in many others, and while it runs counter to the intention of the circular economy by removing products from circulation, it may nevertheless represent the most effective way of sequestering biogenic carbon from the atmosphere long term in certain circumstances. The landfill scenario in the EN 15804-compliant EPD by FWPA for Australian glulam for example [32] predicts a long-term release from landfill of 62 kgCO2-e/m3, which is just 6% of the biogenic carbon originally sequestered in the wood. The calculation is based on the following assumptions, with technical references provided in the EPD :

- Of the gases formed from any degradation of wood in landfill, 50% is methane and 50% is carbon dioxide.
- 36% of the methane is captured, of which a quarter is flared and three quarters is used for energy recovery.
- Of the methane that is not captured, 10% is oxidised and 90% is released to the atmosphere.
- The 'typical' DOCf (degradable organic carbon fraction) is taken as 0.1%, based on bioreactor laboratory research involving testing of various wood waste types in reactors operated to generate maximum methane yields [33], and informed also by excavation of landfill sites to recover old wood samples [34].

Fig. 5. Filbornaverket in Helsingborg, Sweden, is a modern waste-to-energy incineration plant that uses combustible household and commercial / industrial / demolition waste to produce 78MW of electricity and steam for district heating. It was designed to exceed EU standards for cleanliness of exhaust gases [41]. Around half of Sweden's municipal solid waste is burned for energy recovery at end-of-life, the other half is recycled [42]. Photo : Öresundskraft

Fig. 6. Sections of timber products retrieved from a Sydney landfill site after 46 years of burial [34].

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This suggests a remarkable potential for indefinite carbon storage, though assumptions regarding landfill management practices will vary with country and industry practice, particularly regarding methane capture, flaring, and energy recovery. The CO2-e calculation is sensitive to the DOCf assumption, and it relies on the anaerobic conditions commonly found in Australian landfill sites, which will also not be universal.

System Boundaries

In an LCA under EN 15978, a full building system boundary contains Modules A to C, with the 'supplementary' Module D covering the benefits and loads considered to be beyond the system boundary, by giving credit for avoided future use of primary materials and fuels [7]. Module D needs to be reported separately and not aggregated with Modules A to C [49].

Sourced from sustainably managed forests, timber in buildings is generally considered to have biogenic carbon neutrality, meaning biogenic carbon is accounted for when entering (Module A1) and leaving a building (Module C3/C4), producing a net zero effect [29]. In the case of re-use or recycling, carbon benefits are accounted for in the downstream processes of any subsequent product through reduced Module A1-A3 emissions. For European timber products, where Module D energy recovery through incineration is common practice, the benefit is also beyond the system boundary and becomes a broader circular economy benefit. On the other hand, long-term carbon storage in landfill sits in Module C4 and thus within the system boundary of the current project. Adopting the EPD in [32] for example, the landfill option therefore means a considerable biogenic benefit for the current project, compared to the re-use scenario where EN 16485 implies zero benefit, as the captured carbon is passed on. For the current project, landfill therefore wins over re-use, which is at odds with the intent of the circular economy.

The purpose of this discussion about EOL is to highlight the impact that choice of LCA system boundaries can have on allocation of biogenic carbon benefits and therefore the importance of providing a verbal account of project EOL carbon transfer options in addition to the strictly numerical account.

7. POLITICAL DRIVERS

At the international level, a key outcome from the 2021 COP26 in Glasgow was the ratification of Article 6 of the 2015 Paris Agreement, thereby opening the way for international trading of carbon credits via ITMO's (internationally transferred mitigation outcomes), to assist countries in meeting their NDC's (nationally determined contributions) under the Agreement. Applied to forest management for example, this could have big implications for inward investment into countries under pressure to reduce deforestation, such as African countries in the Congo basin, where the world's largest carbon sink is under threat [35,36].

At the national level, governments that have adopted carbon tax or cap-and-trade systems are best placed to monitor and control their progress toward their NDC. Applied to the construction sector, cap-and-trade or other carbon pricing mechanisms will over time favour the transition to greener materials and construction practices [37], providing a market advantage for construction in timber.

Climate Change Conferences (COP's) also host gatherings of regional and city leaders, who continue to advance their own abatement plans alongside national plans. In some local and regional jurisdictions 'timber first' policies have been introduced, including Canada, New Zealand, Germany, Finland, USA, Australia. In most instances there was an active local forest industry advocating, with notable exceptions like the London Borough of Hackney, where the council adopted its policy in 2012 and now has 24 of the UK's largest timber buildings [38].

Some policies have mandated the use of wood in buildings funded with public resources (Canada, France, Sweden); other policies at local government level in Sweden and Finland have required the use of timber on certain sites, and others have funded R&D through public competitions (Austria, Germany, Canada, USA, Norway). Japan introduced its Wood First Law in 2010, which obliges national and local government to use wood for public buildings of three storeys or less [40].

While governments grapple with emissions policy, voluntary green building ratings schemes continue to have a positive effect. These schemes have been evolving too: LEED and BREEAM have moved to recognise LCA as a key assessment tool, thereby allowing more accurate quantification of timber's carbon sequestration potential.

8. CONCLUSION

Construction in timber will not be a primary driver of emissions abatement, but it will make a useful contribution and can also serve as a catalyst for better forest management. The wider adoption of LCA as a criterion for assessing the carbon performance of construction in different materials will be important in maximising the sequestration potential of timber buildings. As part of that, understanding end-of-life choices and their effect on life-cycle outcomes will also be important. LCA conventions that allow credit for biogenic carbon storage to be allocated equitably across building projects will allow clearer present-day choices to be made between the benefits of different construction materials.

Increasingly, an important catalyst for timber building uptake will be government leadership in setting CO2 abatement policy, through stricter implementation of carbon pricing schemes as key platforms for achieving nationally determined contributions under the Paris Agreement.

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