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Lifecycle carbon implications of conventional and low-energy multi-storey timber building systems

Ambrose Dodoo*, Leif Gustavsson, Roger Sathre

Sustainable Built Environment Group, Department of Built Environment and Energy Technology, Linnaeus University, Växjö SE-35195, Sweden

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ABSTRACT

A consequential-based lifecycle approach is used here to explore the carbon implications of conventional and low-energy versions of three timber multi-storey building systems. The building systems are made of massive wood using cross laminated timber (CLT) elements; beam-and-column using glulam and laminated veneer lumber (LVL) elements; and prefabricated modules using light-frame volume elements. The analysis encompasses the entire resource chains during the lifecycle of the buildings, and tracks the flows of carbon from fossil energy, industrial process reactions, changes in carbon stocks in materials, and potential avoided fossil emissions from substitution of fossil energy by woody residues. The results show that the low-energy version of the CLT building gives the lowest lifecycle carbon emission while the conventional version of the beam-and-column building gives the highest lifecycle emission. Compared to the conventional designs, the low-energy designs reduce the total carbon emissions (excluding from tap water heating and household and facility electricity) by 9%, 8% and 9% for the CLT, beam-and-column and modular systems, respectively, for a 50-year lifespan located in Växjö. The relative significance of the construction materials to the fossil carbon emission varies for the different energy-efficiency levels of the buildings, with insulation dominating for the low-energy houses and plasterboard dominating for the conventional houses.

1. Introduction

Growing evidence suggests that increasing atmospheric concentration of greenhouse gases (GHGs) is affecting the global climate system. According to the fifth assessment report of the Intergovernmental Panel on Climate Change (IPCC) [1], atmospheric concentrations of carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) have increased about 40%, 150% and 20% compared to pre-industrial levels, respectively. These increases are primarily attributed to combustion of fossil fuels which account for 82% of the world's energy supply, and secondarily to non-energy related activities including industrial process reactions and land-use practices [1]. Worldwide, energy supply and end-use account for 84% of all CO_2 emission [2] and for two-thirds of all GHG emissions [3]. Fossil gas, oil and coal were responsible for 20%, 36% and 43%, respectively, of the total CO_2 emission from fossil fuel combustion in 2010 [4]. Both globally [5] and within the European Union (EU) [6], electricity generation is dominated by stand-alone condensing power plants fuelled by fossil energy resulting in large excess of waste heat and CO_2 emission. The International Energy Agency (IEA) anticipates that global CO_2 emission may increase by 20% by 2035 with the current trends in energy use and planned measures to mitigate climate change [1]. This might result in a global average temperature rise of 3.6 °C (relative to pre-industrial levels) [3], much more than the 2 °C limit suggested to avoid dangerous climate change [7]. It is estimated that stabilization of atmospheric GHG concentrations at around 450 ppm CO_{2eq} may lead to a 50% chance of achieving the 2 °C limit [8].

A variety of strategies can be adopted to facilitate a transition from a society driven mainly by fossil fuels and non-renewable resources to one driven mostly by low-carbon fuels and renewable resources exploited at a sustainable rate. These include energy-efficient buildings, substitution of material and fuel with less carbon-intensive alternatives, improved efficiencies in energy supply chains and efficient management of post-use materials. The building sector accounts for a large share of global CO_2 emission and is a major focus in the ongoing efforts for climate change mitigation [9]. About 33% of the total global CO_2 emission is linked to

* Corresponding author. Tel.: +46 470 767812; fax: +46 470 768540.
E-mail address: ambrose.dodoo@lnu.se (A. Dodoo).

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energy use in buildings [10]. A non-energy related CO_2 emission also linked to the building sector is from the calcination reaction that occurs during the manufacture of cement. Globally, cement production accounts for about 5% of all anthropogenic CO_2 emission, of which nearly half is from the calcination process and the remainder from fuel combustion [11]. The IEA suggests that the building sector presents one of the lowest GHG mitigation costs [12].

Greater use of wood-based materials from sustainably managed forests is increasingly identified as an effective means to reduce fossil energy use and to mitigate climate change. For example, increased use of wood products is suggested as an important potential contributor to efforts to tackle climate change in the EU [13]. Sathre and Gustavsson [14] noted that sustainably produced wood products can significantly reduce fossil fuel use and give low climate-related external cost. A similar conclusion was reached by Sathre and Gustavsson [15] in a state-of-the art review of climate implications of wood-based products substitution. The IPCC [16] highlighted the critical role that wood products substitution can play in the ongoing efforts to create a built environment with low climate impacts, and suggested options to increase the climate benefits of wood products. The options include improved quality and processing efficiency of wood products and effective post-use management of wood materials. Great climate benefits are achieved at the very end-of-life of wood materials if they are used for energy purposes instead of fossil fuels [17]. Gustavsson et al. [18] reported that the carbon mitigation efficiency of wood is significantly better if it is used to replace a non-wood building material than if it is used directly as bioenergy. Reid et al. [19] summarized evidence related to the use of wood-based products for climate change mitigation. They noted that besides climate change mitigation, increased use of wood-based products could give additional economic, environmental and social benefits.

Several comparative studies of climate implications of materials show that wood-based products result in less energy use and low carbon footprint [20–29]. Lippke and Edmonds [20] compared the carbon implications of alternative walls and floor construction systems with wood or concrete and steel components. They found that the wood-based system has significantly less carbon emission. Buchanan and Honey [21] examined the CO_2 implications of different construction systems including buildings with reinforced concrete, steel or wood structural frames. They found that fossil carbon emitted during the production of the wood buildings is significantly less than that for the non-wood alternatives. Nässén et al. [22] showed that a wood-frame building results in lower carbon emission than a concrete-frame building under the current European production and energy systems. Lippke and Edmonds [23] showed that external walls with wood-based assemblies have lower climate impact than alternatives with steel-based assemblies for different US climates. Gong et al. [24] found that a wood-frame building has much lower production and lifecycle CO_2 emission compared to a concrete frame or a light-gauge steel frame alternative. Dodoo et al. [25] showed that a wood-based building has a lower lifecycle impact than a concrete-frame alternative also if the impact of thermal mass is taken into account. Lippke et al. [26] summarized the lifecycle implications of wood utilization and reported that sustainable reduction in atmospheric carbon is achieved when wood substitutes for fossil-intensive products such as steel and concrete. Petersen and Solberg [27] showed that considerable GHG emission is avoided when solid wood flooring substitutes non-wood alternatives including linoleum, vinyl, polyamide or wool carpets. Eriksson [28] performed a review of lifecycle impacts of different construction methods. The findings suggest that substitution of wood-based building materials for steel and concrete alternatives is beneficial from a climate perspective. Perez-Garcia et al. [29] showed that carbon emission for production of a US house is significantly reduced when it is constructed with wood instead of concrete or steel frames. They noted that further carbon reductions for wood-based buildings are possible through e.g. intensive forest management practices and improved management of post-use wood materials.

In contrast to alternative materials, relatively little fossil energy input is needed to manufacture wood-based building products [30,31]. Large amounts of woody residues can be obtained during the lifecycle of wood products, and this can be used in place of fossil energy [32]. Temporary sequestration of carbon in wooden materials and avoidance of CO_2 emission from calcination reaction are other dynamics by which the use of wood-based materials may reduce climate impacts [33]. In a meta-analysis integrating data from 21 wood substitution studies, Sathre and O'Connor [34] calculated the average emission reduction achieved when a tonne of dry wood is used in place of non-wood products to be 3.9 t CO_{2eq}. Sathre and Gustavsson [15] projected that full scale wood substitution for European multi-family and single-family buildings could reduce annual GHG emission by 1.2% and 0.29%, respectively. Effective management of forest and wood residues are essential to optimize the carbon benefits of wood substitution [34].

Increasing recognition of the low carbon footprint associated with wood-based materials has heightened interest in multi-storey buildings with timber-frames [35,36]. In Sweden, timber multi-storey building construction declined due to a century-old legislation which prohibited such construction until its repeal in 1994 [37,38]. Conventionally, timber multi-storey buildings are constructed using light-framing systems and recently new forms of timber multi-storey building systems have been developed [17,39–41]. While several comparative lifecycle studies on timber vs. non-timber building systems have been reported in literature [22–28,42], few comparative analyses have been reported on the climate implications of different timber building systems or modern timber construction techniques. Aye et al. [43] compared the lifecycle GHG performance of three multi-storey building systems including a modular prefabricated timber building. The production and operation stages of the buildings are considered in the analysis. Quale et al. [44] compared the lifecycle global warming potentials of residential timber buildings constructed with conventional construction or off-site fabricated modular systems. The analysis considered the impacts of material production, on-site and off-site construction activities, transportation and waste management. Monahan and Powell [45] explored the cradle to site CO_2 emission for production of two residential buildings including an off-site fabricated modular timber frame building. Salazar and Meil [46] compared the carbon balances of two residential building alternatives including a typical timber house with conventional materials and a timber-intensive house with full substitution of wood in place of non-wood alternative materials. They accounted for carbon flows from forest management, material production, construction and end-of-life management of the buildings. John et al. [39] conducted a carbon footprint analysis of new forms of timber multi-storey building systems using laminated veneer lumber (LVL) structural elements. Kim [47] conducted a partial lifecycle assessment of residential timber-frame buildings using off-site fabricated modular system or conventional site-built system. The analysis considered the production and the operation stages but excluded the end-of-life stage of the buildings. Barrett and Weidmann [48] compared the carbon footprint of a conventional on-site built house and an off-site manufactured house which maximised the use of timber. The analysis considered the impact from materials, transport, maintenance, and from the occupation of the houses. Still, most reported studies did not include the complete building lifecycle. A system-wide analysis including all significant carbon flows through