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Lifecycle primary energy analysis of low-energy timber building systems for multi-storey residential buildings

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ABSTRACT

A system-wide lifecycle approach is used here to explore the primary energy implications of three timber building systems for a multi-storey building designed to a high energy-efficiency level. The three building systems are: cross laminated timber, beam -and-column, and modular prefabricated systems. The analysis considers the energy and material flows in the production, use and post-use lifecycle stages of the buildings. The effects of insulation material options and the contribution of different building elements to the production energy for the buildings are explored. The results show that external and internal walls account for the biggest share of the production energy for all building systems and its contribution is comparable for the different systems. In contrast, there is significant variation in the production primary energy for the roof-ceilings and intermediate floor-ceilings for the different building systems. Overall, the cross laminated timber building system gives the lowest lifecycle primary energy balance, as this building is insulated with stone wool and has better airtightness in contrast to the other building systems which are insulated with glass wool and have lower airtightness performance. With improved airtightness and insulation substitution, the total primary energy use for the beam-and-column and modular building systems can be reduced by 7% and 9%, respectively.

1. Introduction

Non-renewable fuels currently supply about 87% of the global total primary energy [1], with fossil fuels accounting for 82%, to which oil, coal and fossil gas contribute 32%, 29% and 21%, respectively [2]. Within the European Union (EU), oil, coal and fossil gas provide about 37%, 16%, and 25% of the total primary energy use, respectively [3]. The International Energy Agency global energy system scenarios for 2009–2035 anticipate that fossil fuels may increase in use and remain the dominant energy source [4]. Moreover, long-term energy mix scenarios by the Intergovernmental Panel on Climate Change suggest that fossil fuels are likely to contribute at significant levels in the year 2100 [5].

In the EU where buildings account for 41% of the total final energy use, efforts are ongoing to improve buildings energy efficiency and thereby reduce dependency on fossil fuels [6,7]. Low-energy buildings constitute an important part of the portfolio of measures to improve energy efficiency in buildings in many European countries. Low-energy buildings have much improved operational final energy performance compared to code compliant buildings in a given country. They encompass various standards and criteria including passive house, self-sufficient house and zero energy house. In Sweden, the LÅGAN project documented a classification system for low-energy buildings, and defined such buildings to encompass buildings with at least 25% lower specific purchased energy compared to the requirements of the prevailing building code [8,9]. Generally, low-energy building standards and criteria emphasize the use of both active and passive technologies to minimize heat losses in buildings. Measures typically used to minimize heat losses include improved thermal envelope insulation, reduced thermal bridging, high-performance windows, airtight building envelope and heat recovery of exhaust ventilation air.

Studies from various countries have reported substantial energy savings for buildings designed or built to low-energy standards instead of conventional standards. Dodoo and Gustavsson [10] showed that the final energy use for space heating and ventilation of a Swedish residential building could be reduced by 22% when it is designed to the energy efficiency level of passive house instead of the building code of 2012. Lewandowskaa et al. [11] showed that the overall energy demand of a Polish residential building could be reduced by a factor of 3.6 when it is built as passive house instead of as conventional house. Blengini and Di Carlo [12] reported that space heating demand of an Italian residential building is reduced

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by 91% while lifecycle energy use is reduced by 35% with low-energy instead of conventional building code requirements.

While low-energy buildings result in operational energy reduction, the energy use for building production is increased and becomes more significant [12–14]. Lifecycle studies show that the production stage of a low-energy building may constitute a substantial share of the total lifecycle primary energy use, depending on a building's location, climate, energy supply system and lifespan, as well as on methodological choices. In a hybrid lifecycle analysis of a Belgian residential building, Stephan et al. [15] estimated the production stage of a passive house to represent 77% of the total primary energy for production and operation of the building for 100 years. Thormark [16] found the production stage of a Swedish low-energy house to account for 45% of the total lifecycle energy use for 50 years, based on a bottom-up lifecycle analysis. Dodoo et al. [17,18] performed a process-based lifecycle analysis of Swedish buildings, and found the contribution of the production stage of a passive house to the total primary energy for production, space heating and ventilation for 50 years to range from 20% to 30%. They found that the relative contribution of the production stage depends on the choice of heat supply and is greater when more efficient heat supply systems are used.

Strategies to reduce the primary energy used for production of low-energy buildings are therefore important. Appropriate selection of building materials and structural systems may give significant reductions in lifecycle primary energy use and climate impact of buildings [19–22]. Reviews of lifecycle studies of buildings have underscored the energy and climate benefits of wood-based building materials in contrast to non-wood alternatives [23–25]. Comparatively, wood-based materials require less energy input for manufacture than non-wood alternatives. Significant amounts of biomass residues are generated during the lifecycle of wood-based material and this is increasingly used as bioenergy, and as processing energy for wood-based materials [25–27].

Wood is commonly used for single-family buildings in Sweden, where strong experience exists for such construction [28,29]. However, the Swedish multi-storey building sector is largely dominated by concrete-frame building systems, as the regulatory regime prohibited the construction of multi-storey buildings with timber frames until 1994 [30,31]. Interest in timber-frame multi-storey buildings is now increasing due to growing awareness of environmental impacts of the built environment and the environmental benefits of wood-based materials [32]. Light-framing systems are conventionally used for multi-storey timber buildings in Sweden. In recent times other innovative timber multi-storey building systems are emerging, including those with prefabricated elements, massive timber and engineered timber structural systems. Various studies have been conducted on lifecycle energy and environmental performance of buildings [e.g. 33–42]. While many comparative lifecycle studies have been reported on timber vs. non-timber building systems, few detailed comparative analyses have been reported on the energetic implications of different timber building systems or modern timber construction techniques. Monahan and Powell [43] investigated the lifecycle primary energy use of a low-energy UK building using a modern off-site panellised timber-frame system and compared it to a traditional alternative using on-site masonry construction system. In a US study, Salazar and Meil [44] analysed the primary energy balances of alternative designs for a timber-frame building with different wood intensity and usage. Kim [45] compared the lifecycle energy performance of timber-based buildings constructed with prefabricated modular or on-site conventional building systems in the U.S. John et al. [46] performed an environmental lifecycle analysis including two timber multi-storey building systems using laminated veneer lumber (LVL) in Australia. Beyond these initial studies, little is known about the lifecycle energy implications of innovative timber building systems, considering variations in structural elements, extent of prefabrication and range of wooden materials and components.

In this study we investigate the primary energy balances over the lifecycle of a Swedish multi-storey building designed with three different timber building systems: cross laminated timber (CLT), beam -and-column, and modular volume element. The primary energy analysis includes the entire energy and material chains from the extraction of natural resources to the delivered final energy or

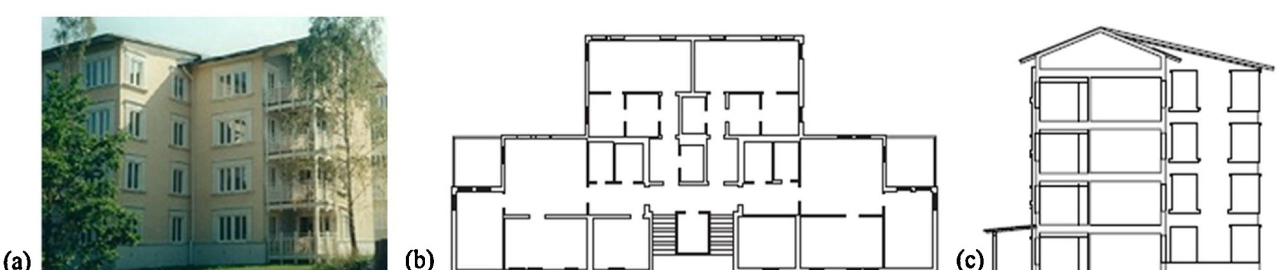

Fig. 1. Photograph (a) and sketch of ground floor plan (b) and vertical section (c) of the reference building.

Fig. 2. Photograph and details of some structural elements of the studied building systems including the (a) CLT building system (b) beam -and-column building system and (c) modular volume element building system.