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Life cycle primary energy use and carbon footprint of wood-frame conventional and passive houses with biomass-based energy supply

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HIGHLIGHTS

- Energy use and carbon footprint of conventional and passive houses are analyzed.
- Passive house reduces the primary energy use and carbon emission for heating.
- The significance of the reduced heating depends on the type of energy supply system.

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ABSTRACT

In this study the primary energy use and carbon footprint over the life cycle of a wood-frame apartment building designed either conventionally or to the passive house standard are analyzed. Scenarios where the building is heated with electric resistance heaters, bedrock heat pump or cogeneration-based district heat, all with biomass-based energy supply, are compared. The analysis covers all life cycle phases of the buildings, including extraction of raw materials, processing of raw materials into building materials, fabrication and assembly of materials into a ready building, operation and use of the buildings, and the demolition of the buildings and the post-use management of the building materials. The primary energy analysis encompasses the entire energy chains from the extraction of natural resources to the delivered energy services. The carbon footprint accounting includes fossil fuel emissions, cement process reaction emissions, potential avoided fossil fuel emissions due to biomass residues substitution and end-of-life benefit of post-use materials. The results show that the operation of the building accounts for the largest share of life cycle primary energy use. The passive house design reduces the primary energy use and CO_2 emission for heating, and the significance of this reduction depends on the type of heating and energy supply systems. The choice of end-use heating system strongly influences the life cycle impacts. A biomass-based system with cogeneration of district heat and electricity gives low primary energy use and low carbon footprint, even with a conventional design. The amount of biomass residues from the wood products chain is large and can be used to substitute fossil fuels. This significantly reduces the net carbon footprint for both the conventional and passive house designs. This study shows the importance of adopting a life cycle perspective involving production, construction, operation, end-of-life, and energy supply when evaluating the primary energy use and climatic impacts of both passive and conventional buildings.

1. Introduction

A transition to a low-energy society based on renewable resources is a major challenge and will require efficient use of energy, from the natural resources to final services. The current global energy system is heavily dependent on fossil fuels, with coal, oil and fossil gas accounting for 27%, 33% and 21% of the total primary energy use world-wide in 2010, respectively [1].

The building sector accounts for about 40% of global primary energy use, and building energy use accounts for about 33% of total global carbon dioxide (CO_2) emission [2,3]. Energy is used during the life cycle of buildings for material production, transport, construction, operation, maintenance and demolition. CO_2 is emitted from fossil fuel combustion, land-use practices and industrial process reactions. There is large potential to improve the primary energy efficiency of buildings and thereby reduce CO_2 emission [4]. Reducing the energy use of buildings also presents a low cost for greenhouse gas (GHG) emission mitigation [5]. Several strategies can be

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used to realize this potential, including the use of woody biomass as both building material and fuel.

Wood-based products from sustainably managed forests can play an important role in reducing energy use and GHG emission [4]. Less energy, in particular fossil fuels, is needed to manufacture wood-based building materials compared with alternative non-wood materials [6–10]. Wood-based materials use primarily biomass residues for processing energy and have lower GHG and primary energy balances than non-wood alternative materials [11]. Wooden materials also store carbon during their lifetime, temporary sequestering carbon from the atmosphere. Large amounts of biomass residues are produced during the manufacture and end-of-life of wood products, and these can be used to replace fossil fuels [11,12]. Biomass is a limited resource and should be used efficiently. Efficient use of wood products involves material and energy flows in different sectors including forestry, manufacturing, construction, energy and waste management. Closer integration of flows from these sectors can improve the system-wide life cycle environmental performance of wood-based products. Accurate analysis across this broad range of sectors is a complex issue and can be problematic [13].

Life cycle studies show that wood-based building materials can results in lower primary energy use and CO_2 emissions compared to alternative non-wood materials such as concrete and steel. Buchanan and Honey [9] compared the CO_2 emission from production of wood-, steel- or reinforced concrete-framed versions of several different types of buildings. In all cases they found that the wood-framed buildings emitted less fossil and process emissions during material production. Dodoo et al. [10] compared the life cycle primary energy balances of functionally equivalent wood- and concrete-framed buildings, including the effect of thermal mass. They found the wood-framed building to have less life cycle primary energy use, even when the impact of thermal mass is accounted. The Consortium for Research on Renewable Industrial Materials (CORRIM) compared the energy and GHG balances of concrete- and steel-framed houses to functionally equivalent wood-framed houses, and found the wood alternative to have lower balances in all cases [14,15]. Sathre and O'Connor [6,16] reviewed several studies on the GHG impacts of wood product use and conducted a meta-analysis of the displacement factors of wood products substituted in place of non-wood materials using data from 21 different international studies. The studies agree that substituting sustainably-produced wood products in place of non-wood products reduces GHG emission.

Life cycle studies have produced varying conclusions on the significance of the production phase of buildings, due to varying system boundaries and regional and technological differences of the studies. Scheuer et al. [17] studied a conventional US building and found material production and building construction to account for 3% of the total life cycle climate impact. Adalberth [18] found the production energy to account for 15% of the total life cycle primary energy use in a conventional Swedish building. Gustavsson and Joelsson [19] found the production energy to account for 4% and 13% of the life cycle primary energy use for a conventional and a passive house in Sweden, respectively. Thormark [20] analyzed a low energy building in Sweden and found the production phase to account for 45% of the total life cycle primary energy use.

Operation energy use can be significantly reduced when a building is designed and built to the passive house standard. Key measures to achieve the passive house standard include improved thermal envelope insulation and airtightness, efficient windows, heat recovery from exhaust ventilation air and efficient water taps and electric appliances. In Sweden, maximum purchased energy of 45 and 55 kW h/m^2 year for the South and North Climate zones (Fig. 1), respectively, is required to meet the passive house criteria [21]. The maximum purchased energy includes space heating, domestic hot water and electricity for fans and pumps but exclude electricity for lighting and household appliances.

Measures to achieve the passive house standard also increase material use and the production energy use. Life cycle studies of buildings show that the energy for material production becomes increasingly significant as measures are applied to reduce the energy for operation [22]. In a study of two houses, Feist [23] reported that the house with lower operational energy had greater overall life cycle energy use because of its high production energy. Hence although decreasing the operation energy is essential, a focus solely on the operation phase may bring less overall benefits due to potential trade-offs in other life cycle phases. A building's life cycle encompasses production, operation and end-of-life phases, which are interlinked. The primary energy use also depends on the energy supply systems. The energy used in a building can be provided by different types of supply systems resulting in a large variation in primary energy use and CO_2 emission for a given final energy use [19]. A comprehensive approach to analyze the impacts requires a system-wide perspective, including all life cycle phases of a building and the entire energy chains, from natural resources to final energy services.

In this study we analyze the primary energy use and carbon footprint over the life cycle of a wood-frame building, designed either conventionally or to the passive house standard. We explore the impact of different end-use heat supply systems on the primary energy use and carbon footprint of the buildings. We analyze cases where the buildings are heated with electric resistance heaters, bedrock heat pump or cogeneration-based district heat, all with biomass-based energy supply. The conventional building is designed according to the energy efficiency regulations of the current Swedish building code [24] while the passive house is designed to meet the energy efficiency requirement of the Swedish passive house criteria [21].

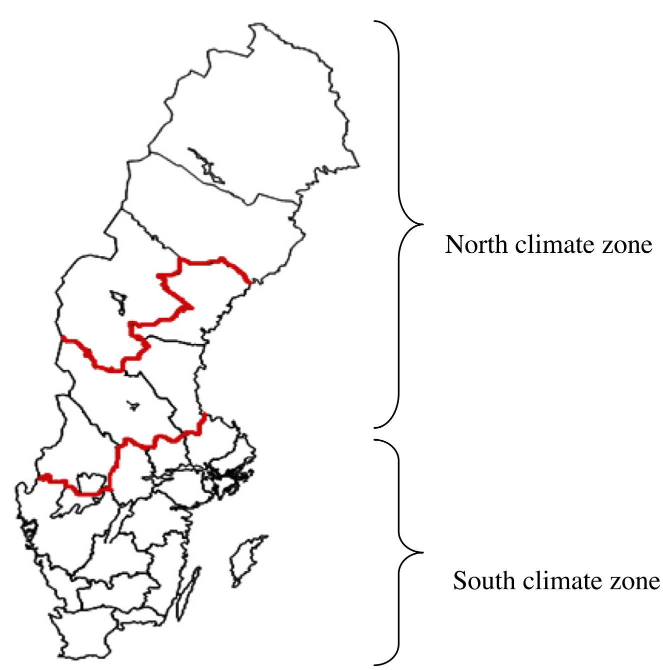

Fig. 1. Swedish climate zones for passive house criteria.