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Life cycle energy balance of residential buildings: A case study on hypothetical building models in Finland

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ABSTRACT

This study has demonstrated the life cycle primary energy balance of the four residential building types (detached house, row house, townhouse and apartment block) based on current Finnish design. The differences in the energy balance arising from the geometrical characteristics of each housing type were investigated using hypothetical building models. In addition, the influence of structural frame material selection was observed in relation to the housing types. The results showed that there are clear differences between the housing types: the detached house is the highest energy consumer, the row house the second (about 20% less), the townhouse the third (about 30% less) and the apartment block the lowest (about 45% less), regardless of the frame materials selection. The differences appeared evenly among the building life cycle stages. A correlation has been observed between the geometrical factors and life cycle primary energy balance of the reference buildings.

1. Introduction

The building sector significantly contributes to the overall environmental impact of humankind's activities. For instance, the sector globally accounts for more than 40% of the total primary energy consumption [1]. In this context, the life cycle energy use and associated environmental impacts of buildings have been intensively studied over the past few decades. Buildings need energy for their construction (embodied energy) as well as their functioning (operational energy). In the effort to reduce the life cycle energy consumption of buildings, most attention has thus far been paid to operational energy because of its dominance. In the case of conventional buildings, in many cases the operational energy accounts for more than 70% of the life cycle energy [2–5]. As a result of efforts in this area, such as improvements of the thermal insulation performance of the building envelope and the development of building service equipment, the operational energy demand has been significantly mitigated. Although the operational energy is still responsible for the major part of the life cycle energy use of buildings, the relative importance of embodied energy has increased, for instance, accounting for up to 46% of the life cycle energy use (service life of 50 years) in the case of low-energy buildings [6–10]. In addition, the nearly zero-energy buildings (nZEBs) will become the norm for all new buildings in the European Union (EU) by the end of 2020 [11], meaning that the life cycle aspect is becoming more important in the discussion of building sustainability. As building operation becomes efficient, the relative importance of the other life cycle phases becomes higher and several aspects (e.g. type of energy use, metric of balance) are recently discussed in the definition of nZEB [12,13]. For instance, as D'Agostino schematised [13], the embodied energy is one of the main arguments around the nZEB concept at the moment.

Although the energy consumption trend varies depending on countries, in many cases, residential buildings are responsible for a major part of the energy consumption of the building sector [14,15]. Due to population growth and economic development, the construction of residential buildings can be expected to increase in the years to come. For instance, in Finland, the population in Helsinki has thus far been steadily growing, and it has been predicted to increase about 8% between 2013 and 2022 because of immigration and domestic migration based on economic growth [16]. Housing supply has, therefore, been being a main topic in the city planning. In principle, a living environment that has a peace, quietness and closeness to nature is preferred by most Finns [17]. Thus, low-density housing area development has occurred in the outer suburbs, especially from the 1990s; as a consequence, the Helsinki region has become among the most sprawling city regions in Europe [18]. In response to urban sprawl, recently dense and diverse residential area development has been aimed by incorporating several housing types to control the compactness and living

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condition of city districts [19]. In addition, the aims for sustainable urban development have been included in the city's action plan since 2002, and sustainable strategies (e.g. energy-efficient buildings and urban structure) have become a top priority in the field of urban development [20,21].

In this context, it is important for the decision making in city planning to understand the environmental features of different residential building types. Although a number of life cycle assessment (LCA) studies have been conducted to estimate the environmental profile of buildings, there have thus far been few studies that have investigated a relative relationship between different residential building types. For instance, Rosa et al. [22] have studied the life cycle environmental impacts (mainly global warming potential (GWP)) of the most common types of house in the UK: detached house, semi-detached house and terraced house. They reported that the semi-detached house and terrace house respectively emitted about 82% and 68% of greenhouse gas (GHG) compared to the detached house over the 50 years of building service life. The major differences between the three houses were caused from the use stage of the buildings. It was noted that the emissions arising from household appliances and water heating highly relate to the number of occupants in the house, whilst the emission from space heating and lighting mainly depends on the physical features of the house, such as composition, size, geometry, material, etc. Nemry and Uihlein [23] compared the environmental impacts of residential buildings (single-family houses, including two-family houses and terraced houses, multi-family houses and high-rise buildings) covering both existing and new constructions in the EU-25, for the 40 years of building service life. The study reported quite similar results as Rosa et al. [22], where, in general, single-family houses showed the highest impacts and high-rise buildings the lowest, regardless the climate zones and either new or existing construction. Gustavsson and Joelsson [24] simulated the life cycle primary energy balance of residential buildings (single family house, row house unit and apartment block) in Sweden for a period of 50 years. They also studied the influence of building material selection and different energy supply systems to discuss potential life cycle energy improvements. Although it is difficult to observe the differences between the housing types, due to significant variations in energy performance of the reference buildings, this study clearly demonstrated that the choice of energy supply system had greater influences than the energy efficiency building envelope measures. It showed that conventional buildings had the possibility to use less operational energy than the passive house level buildings, depending on the choice of energy supply system. The energy supply system also influences life cycle cost balance of a building (e.g. initial and operational cost, payback period) as demonstrated, for instance, in [25].

The material selection directly influences the environmental profiles of a building, since a building is a complex system consisting of many different materials. Several studies, therefore, have thus far been carried out to investigate the relationship between the building material selection and the resulting impacts. Thormark [26], for instance, studied the effect of material choice on both the embodied energy and recycling potential in an energy-efficient apartment block in Sweden. She noted that embodied energy could be reduced by approximately 17% or increased by about 6% by a simple material substitution. Cole [27] investigated the influence of material choice on the construction process. He found that the steel structure consumed the lowest energy during construction and the concrete structure the highest (the concrete structure requiring up to 40 times more energy than the steel construction). Wood construction typically required 2–3 times more construction energy than steel. Although this study is rather dated, it shows an interesting aspect. The effects of material selection on the operational energy have also been investigated [28–31]. It was commonly noted that a heavy-weight structure (e.g. concrete and brick) required less space heating energy (about 1.0–2.0% less) than a light-weight structure (e.g. steel and timber frame) thanks to thermal mass effect. The recycling aspect, which is highly related to the material selection as well, has been highlighted as being a potentially significant factor in reducing the life cycle energy use of buildings [12,26].

2. Objectives and scope

The objective of this study was to investigate the life cycle primary energy balance of residential building types: detached house, row house, townhouse and apartment block, in a Finnish context. A quantification of the differences in the life cycle energy efficiency arising from the compositional features of each housing type was the aim, as a case study in a cold climate area. The entire building life cycle, the production, operation (including maintenance) and end of life (EoL) stages, was covered, and the net primary energy benefits resulting from the reuse and recycling of materials exiting the system boundary was described as a potential resource for future use in accordance with [32]. In addition, this study was carried out in a comparative manner based on four structural frame materials typically used in Finland in order to observe the results in relation to the material selection. Understanding the relative life cycle energy profiles of the residential buildings would aid informed decision-making by professionals associated with the city planning and building design, leading to improved sustainability in urban development. Building service equipment and furniture were excluded from the calculation, since they were out of the scope of this study. Although, as Gustavsson and Joelsson [24] noted, the energy supply system (e.g. electricity mix, space heating technology, ventilation system) would have a major influence on the life cycle energy balance of a building, that was held constant as it is not within the focus of this study.

3. Methodologies

3.1. Reference building models

Simplified hypothetical building models reflecting the compositional features of four housing types, detached house (DH), row house (RH), townhouse (TH) and apartment block (AB), were used as the case study. Fig. 1 shows the basic plan and section of the models with an indication of the building elements (e.g. party wall, intermediate floor, etc.). The building models were made based on a common module (6 m*10 m*3 m). Table 1 shows the floor area and the area of each building element used in the calculation. Net heated floor area was used as the functional unit in this study. The

Table 1
Basic information of the reference buildings and surface area of each building element.

	DH	RH	TH	(m2) AB
Apartment	1	3	3	20
Story	2	2	3	4
Gross floor area	120	360	540	1920
Net heated floor area	96	316	475	1775
Foundation + ground floor slab	48	154	154	425
Exterior wall	186	301	453	933
Party wall	0	103	230	684
Interior structural wall	0	0	0	197
Intermediate floor	52	166	166	0
Party floor	0	0	166	1335
Roof	60	180	180	480
Window/Door	10	32	47	178
Staircase	included in the intermediate and party floor			