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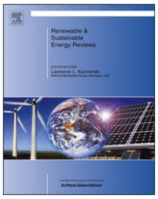

Life Cycle Assessment of embodied and operational energy for a passive housing block in Austria

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ABSTRACT

The creation of a sustainable built environment is related not only to energy-efficient construction but also to the efficient use of materials, in order to minimise environmental impacts and avoid further depletion of natural resources. However, “passive” or “zero-energy” buildings, which optimise operational energy, require additional materials (e.g. insulation) or the installation of technologies (e.g. mechanical ventilation) which further increase the embodied energy of the building and related environmental emissions.

This paper questions the environmental impact and benefits of adding materials and technologies in order to reduce the energy consumption of a building by evaluating the embodied and operational energy of a case study of a passive housing block in Austria. The analysis is carried out using real data, based on energy monitoring carried out over three years, and on original documentation of the materials and construction of the building. Applying a Life Cycle Assessment (LCA) method, the environmental impacts of the building materials, the heating, ventilation and air-conditioning (HVAC) technologies, and the operational energy were assessed and compared for time scenarios of 20, 50 and 80 years using the environmental indicators: Global Warming Potential (GWP); Primary Energy Intensity (PEI); and Acidification Potential (AP).

Two different variants of the “as built” building were modelled and investigated in terms of their ecological impacts. It was found that distribution pipes for building services apparently contributes 10% of the GWP, and the optimisation using timber instead of concrete is advantageous in terms of minimising GWP and AP, but is less effective in terms of PEI.

Finally, the apartment block “as built” to a passive house standard was compared with a low-energy equivalent building in order to question whether the increased input of materials for the passive house is justified in terms of the reduction of the energy demand during the operation of the building. It was found that the passive house performs better in terms of environmental impacts, but not significantly so (max. GWP saving of 7% in the 80 years scenario). The reasons are multifaceted, and include additional heating of the apartments by the occupants, uncontrolled window opening patterns and increased hours of occupancy.

1. Problem statement

Through the development of design methods (e.g. passive, zero energy or even “plus energy” buildings) and building technologies, the energy consumption needed for buildings in operation has been significantly reduced. In order to achieve further reductions of the environmental footprint of buildings the efficient use of materials and building services (e.g. Heating, Ventilation and Air-Conditioning, HVAC) start to play a crucial role. As operational energy is reduced to a minimum by high-performance insulation, air-tight building envelope and high-performance building services, so the amount of embodied energy and related environmental impacts of materials and building products requires optimisation, preferably in the early design stages. With the increasing number of highly energy-efficient dwellings

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Abbreviations: AP, Acidification Potential; AEC, Architecture Engineering Construction; EPD, Environmental Product Declaration; EPS, Expanded Polystyrene (insulation); GFA, Gross Floor Area; GWP, Global Warming Potential; HVAC, Heating, Ventilation and Air-Conditioning; IO-LCA, Input-Output Life Cycle Assessment; LCA, Life Cycle Assessment; LCCO$_2$A, Life Cycle Carbon Emissions Assessments; LCEA, Life Cycle Energy Assessment; LCIA, Life Cycle Impact Assessment; LCI, Life Cycle Inventory; LC_ZEB, Life Cycle Zero Energy Building; LEH, Low Energy House; LEH$_{EC}$, Low Energy House based on predicted demand (as calculated by the energy certificate); MFA, Material Flow Analysis; MVHR, Mechanical Ventilation with Heat Recovery; NFA, Net Floor Area; nZEB, nearly Zero-Energy Building; PEI, Primary Energy Intensity; PEI$_{NR}$, Primary Energy Intensity – Non-Renewable; PEI$_{RE}$, Primary Energy Intensity – Renewable; PH, Passive House; PH$_{AB}$, Passive House As Built, energy performance based on monitored consumption; PH$_{EC}$, Passive House as calculated by the Energy Certificate, energy performance based on predicted demand

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(passive houses) in Central Europe, particularly in social housing, the question this paper addresses is whether it is possible to justify the reduction in operational energy throughout the life cycle achieved through the increased input of materials and building technologies (therefore increased input of embodied energy). The investigation was carried out using a case study of a passive housing block for which the exact material composition, as well as predicted energy demand and actual consumed energy over three years, was available.

Actual energy consumption is seldom monitored, and it is difficult to assess exact material composition of buildings post-construction, therefore the results of this paper represent a novelty in the current body of knowledge on the life cycle impacts of energy-efficient building typologies such as passive houses: the use of an LCA approach based on real monitored energy data in the period of three years on the one hand, and exact tendering documentation on the other. The obtained results will enable designers and investors to optimise their future projects in terms of environmental footprint and total life cycle energy. Furthermore, a comparison of four variants highlights the optimisation potential for state-of-the-art construction and assessment methods, providing exemplary knowledge for future design.

2. Literature review

2.1. Life Cycle Assessment methodology

The need for optimisation of building performance, not only in terms of energy but also in terms of resources consumption, has been recognised by the principle decision makers, planners and investors [1]. In order to achieve sustainability, an assessment of the environmental performance of buildings and the sub-components based on evaluation and optimisation of both embodied and operational energy and emission would be needed in the planning phase [2]. A Life Cycle Assessment (LCA) aggregates and analyses the flows of resources and materials throughout the life cycle of products (from cradle to grave, or even better, from cradle to cradle). Carrying out an LCA for buildings involves major effort due to lack of information about the used materials and their production processes. Manufactured products have standardized production processes, which means that the LCA is easier to accomplish [3].

LCA as defined by the ISO (International Organization for Standardisation) Standard 14040:2006 [4,5] evaluates the direct and indirect energy inputs in each product process. Further, the ISO Standard describes the principles, the framework and temporal and spatial system limits of the LCA. The main phases of LCA are defined as: the goal and scope definition; the inventory analysis; the impact assessment; and the interpretation phase. In the goal and scope definition phase the system boundary and the level of detail is determined. The depth of the assessment is dependent on its goal. The second phase is the Life Cycle Inventory (LCI) analysis phase, which is a documentation of input and output data of the investigated system. The aim of the Life Cycle Impact Assessment (LCIA) phase is to evaluate the environmental significance of potential impacts. In the last phase, the life cycle interpretation phase, the results of the LCI and or the LCIA are discussed and conclusions are made out of them [5].

LCA can be differentiated into two main approaches regarding assessment: the process-based LCA [6,7] and the Input-Output LCA (IO-LCA) [8,9]. The process-based LCA is a bottom-up process analysis, meaning that the system is modelled on the basis of the specific information of the life cycle processes, which consist of raw material extraction, manufacturing, use, disposal and end-of-life treatment [4]. The IO-LCA is based on financial quantities (price of building material) that are linked to an economic sector and maps the flows between the economic sectors and their energy intensity [6,8,10]. Due to the incompleteness of the process analysis and the limitations of the IO-LCA, Bullard et al. [11] proposed a hybrid technique that focused on reducing the truncation error of process-based LCA with the smaller aggregation error of IO-LCA.

A further evaluation method is the Material Flow Analysis (MFA), which is an estimation of the material demand and the environmental impact of a system [12]. Human activities make use of various services provided by stocks of capital and consumer goods, which leads to material and energy flows that interact with the environment during their life cycle stages [13]. The MFA methodology assesses the flow of materials entering and leaving a system and evaluates their impact on the environment [14].

2.2. LCA for buildings

Buildings have an important influence on the worldwide total natural resource and energy consumption [15]. The buildings sector accounts for 40% of the world's energy consumption and for a third of the global greenhouse gas emissions [16].

There are three main approaches to the study of environmental impacts of buildings. One of them is LCA, which focuses on evaluating the total environmental impacts of buildings over their entire life cycle. The second stream of studies can be grouped under the title Life Cycle Energy Assessment (LCEA), which is an evaluation of the energy use and consumption over different stages of a building's life cycle, expressed as primary energy consumption from nature or secondary energy as actual consumed energy [17,18]. The third stream is the Life Cycle Carbon Emissions Assessments (LCCO$_2$A), the objective of which is to evaluate the carbon dioxide (CO$_2$) emissions as an output over the whole life cycle of a building [17].

Numerous LCA tools for the compilation of buildings-related emissions throughout the life cycle are available on the market, such as: the commercial software tools LEGEP or SimaPro; eco2soft provided by IBO (the Austrian Institute for Healthy and Ecological Building) [19] and therefore freeware; and calculation templates proposed by building certification systems such as Deutsche Gesellschaft für Nachhaltiges Bauen (DGNB), Building Research Establishment Environmental Assessment Methodology (BREEAM) or Leadership in Energy and Environmental Design (LEED), which are freely accessible to the public, but not in full extent. In addition, GaBi and SimaPro provide various assessment methodologies from energy to diverse impact category assessments.

The LCA assessment as proposed by building certificates or IBO [19] generally assesses three important indicators for the environmental impacts: Global Warming Potential (GWP); Acidification Potential (AP); and Primary Energy Intensity (PEI), which is divided into Non-Renewable and Renewable parts [19] along the life cycle stages of production or manufacturing of materials, transport, operation (maintenance and replacement) and end-of-life.

The implementation of such thorough analysis methods and tools in Architecture, Engineering and Construction (AEC) practice are still facing various challenges. The reasons are numerous. For example, the existing standards regulate system limits, indicators and the calculation methods. However, the workflow is still too complex to find wide application among planners and decision makers. The tools are generally costly, and lack usability and user-friendliness. The data availability and analysis requires a significant amount of time, which is often not available in the course of standard design, planning and construction processes.

2.3. Embodied energy versus operational energy

Buildings consume energy throughout their various life cycle stages, both directly and indirectly. Direct energy is consumed within the construction process, operation (operational energy), maintenance, refurbishment and demolition. Indirect energy is used for the production of the materials, and for technical installations (embodied energy); as well as for the replacement of elements after their useful life. Sartori et al. [20] defined embodied energy as the sum of the energy that is needed to manufacture a good; and operational energy as the energy