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The relationship between operational energy demand and embodied energy in Dutch residential buildings

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ABSTRACT

Reducing heat demand of buildings, due to legal and technological advances in the EU, shifts the ratio of operational vs. embodied energy towards an increasing share of the latter. This leads to a shifting focus on building materials (embodied) energy use. In this study the relationship between heat demand and embodied energy use was investigated, using Dutch residential buildings as a case study. The analysis was performed using the 3SCEP HEB (Center for Climate Change and Sustainable Energy Policy High Efficiency Buildings) model and a constructed Embodied Energy Database Management System (EEDMS), containing embodied energy use of materials most common in Dutch residential construction. The resulting embodied energy use in Dutch dwelling archetypes varies from 52 to 106 MJ/(m²·a), annualised over building lifetimes and 3.0 to 6.4 GJ/m² in total. These values are for the building construction and exclude recurrent embodied energy and technical installations. For operational energy use the range is 124 to 682 MJ/(m²·a). A total energy use reduction of 36% can be reached in 2050 through 46% reduction in operational energy use and 35% increase in embodied energy use, compared to 2015. This research confirms that the relative importance of embodied energy use is increasing: the embodied energy use in standard homes is about 10–12% of the total energy use, while it is 36–46% in energy efficient homes. Particularly in light of the goal to reach a maximum global temperature increase of well below 2 °C by 2100, it is important to include embodied energy use in future policy objectives.

1. Introduction

The operational energy use of buildings, i.e. the energy required for heating and cooling of buildings [8], leads to about 33% of the total final energy demand globally and to 30% of the global CO_2 emissions related to energy use [60]. Therefore, to reach the target to limit the increase in global average surface temperature to well below 2 °C as compared to pre-industrial levels, greenhouse gas emissions from the built environment should be reduced, especially since these are identified to have the highest potential [24]. There have been significant advances in both technologies and policies to reduce the energy consumption for heating, accounting for the largest share of building energy use in most developed countries. However, this often leads to an increase in embodied energy use, i.e. the energy consumption required to produce the building capital [28,47].

According to Langston and Langston [26], assessing embodied energy is more complex and time consuming than measuring operational energy use. Trusty and Horst [58] used LCA (Life Cycle Assessment) tools like SimaPro and Athena for energy analysis of buildings. However, this LCA approach does not provide an easy way to compare and show the interaction of the different phases of energy use (construction, operation and demolition phase) in buildings, because it usually focuses on the aggregated energy picture.

The embodied energy analyses usually focussed on a specific country or location. For example, Reddy and Jagadish [62] investigated embodied energy in buildings in the Indian context. In this study it was found that by using low-energy intensive materials and other construction techniques in residential buildings, 30–45% reduction in total embodied energy use can be obtained. Takano et al. [55] showed that particularly in low-energy buildings, embodied energy contributes highly to the building life cycle energy with contributions up to 46% of total energy use. Several other studies were done on embodied energy use in

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buildings; Chen et al. [12] investigated the embodied energy use profile in buildings in Hong Kong and Buchanan & Honey [9] investigated this for New Zealand. When considering Europe, most countries seem advanced in increasing the energy efficiency of buildings compared to countries on other continents. But, when the identified energy savings potential is examined more closely, it becomes clear that there is a lack of well-founded data on these potentials, on European and national level [30]. Especially the impact of different deployment pathways for retrofitting and renewing of building stock on total building lifetime energy use on a country level is missing. This study therefore aims to analyse the relationship between operational energy and embodied energy use in residential buildings in a scenario context. This gives information for policy makers on the total impact of building renovation and renewal instead of only the impact on operational energy use. As a case study in this research the analysis is performed for residential buildings in the Netherlands in the period up to 2050. Building regulations in the Netherlands date back to 1901, when the Housing Act was adopted [53]. This Act was extended in 1993 with the Building Decree with national minimum requirements for the energy performance of new buildings measured by the Energy Performance Coefficient (EPC) [37]. By introducing the EPC, the responsibility of choosing energy efficiency measures to realise a particular energy performance in a building, shifted towards the construction industry. This means that buildings can be built with the materials the developer prefers, as long as it meets the requirements given in the Dutch building regulations. The developer is also obligated to include an environmental performance calculation of every newly supplied building (De Klijn-Chevalerias and Javed, 2017). This calculation is meant to stimulate the developer to use sustainable construction materials, but does not enforce any restriction on the amount of embodied energy used in the construction materials. The assessment of the trade-off between operational energy use and embodied energy use will allow decision makers to take a step towards optimisation of the performance of Dutch residential buildings by taking into account the relevance of the choice of construction materials. This will on its turn, contribute to the reduction of energy related CO_2 emissions [51]. This assessment can also be used as an example for other countries to map their embodied energy use.

Embodied energy in this research is defined as the initial energy required to produce the building materials plus transport energy required to transport the materials to the construction site. The *initial* embodied energy depends on the material choice in the building and the manufacturing processes that were needed to produce the material (cradle to gate energy). Also, energy that is directly associated with the construction process, like the transport of materials to the factory site, is included in the embodied energy [49,50]. The *transport* energy is defined as the average primary energy necessary to transport the building materials from factory gate to construction site. In this research, demolition energy (energy necessary to demolish a building at the end of its lifetime) is excluded because this energy is not directly influenced by material choice. Furthermore the demolition stage includes a lot of uncertainties with regard to the fate of a building in the future [48]. According to Crowther [15] and Stephan, Crawford, and de Myttenaere [51] the energy required for demolition, represents however only about 1% of the total life cycle energy of the building. Recurrent energy (energy that applies to the embodied energy of components of the building with a shorter lifetime than the lifetime of the building) is also excluded since it is susceptible to consumer preferences. This makes it difficult to include in an overview of average embodied energy use (see Section 4 "discussion of uncertainties", for possible impacts on results).

2. Method

The research method is based on the joint application of two tools: the Embodied Energy Database Management System (EEDMS) and the $_3$SCEP HEB model.

The Embodied Energy Database Management System (EEDMS) was developed in this study to analyse the embodied energy use in the Dutch residential sector based on 23 materials most commonly used in Dutch residential construction. The tool includes material volumes and material energy intensities for 25 Dutch building archetypes.

The $_3$SCEP HEB model was developed by the Center for Climate Change and Sustainable Energy Policy ($_3$SCEP) to perform a policy-based scenario analysis concerning the global potential of reducing operational energy use and associated greenhouse gas emissions by high efficiency buildings (HEB). This analysis started under guidance of the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) and was extended in cooperation with the Global Buildings Performance Network (GBPN) in 2011 and 2012 [61]. This model simulates the development of the world's building stock and related operational energy use. The building stock is broken down by regions, climate zones, building types and building vintages.

The $_3$SCEP HEB model is used to model the development of the Dutch building stock development in floor area from 2015 to 2050. These outcomes are used as input in the EEDMS to calculate total embodied and operational energy use from 2015 to 2050.

The method consists of three steps, which are further described in the subsections below:

1. Identifying buildings archetypes for the key Dutch building typologies and their operational energy use (Section 2.1)
2. Data collection of average material composition in building archetypes and corresponding embodied energy intensities to calculate embodied energy use (Section 2.2)
3. Modelling floor areas for different scenarios with the $_3$SCEP HEB model (Section 2.3)

2.1. Building archetypes and operational energy use

All residential buildings in the Dutch residential stock are categorised into 25 building archetypes on the basis of two factors: building types and building vintages. Five types of buildings are distinguished that occur most in the Netherlands in 2015 [10]: mid-terrace, end-of-terrace, detached, semi-detached and apartments.

The vintages are based on the construction period and their specific energy performance due to building regulations:

- The *standard* (conventional) vintage category includes dwellings built before 2015. These are based on a selection of building archetypes that are most common in the Netherlands. The dwelling archetypes are built in the period 1965–1974, which reflects the average age of the current building stock and the energy use that is representative for the building regulations in that period [2]. The selected archetypes together account for nearly 20% of the total dwellings in the Netherlands in 2015 (see Table 1).
- The *New* vintage represents an average home that is built according to building regulations set in 2015.
- *Advanced new* represents a building built from 2015 in line with the requirements of a nearly-Zero Energy Building (nZEB) standard. A nZEB is a building with a low energy demand which can largely be met by renewable energy sources at the same location or nearby (European Parliament & EU Council, 2010). In this research this is represented by a passive home (PH), which is a concept to define a nZEB according to the Passive