On the share of embodied energy in the lifetime energy use of typical Hellenic residential buildings

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Abstract. The evolution of the built sector towards nearly zero energy buildings is a key issue in the global effort to reduce the greenhouse effect through the abatement of carbon emissions. For a realistic assessment of the potential for energy consumption and emissions reduction in the built sector, a life cycle approach is deemed necessary. However, the contribution of the embodied energy (EE) and related carbon emissions associated with the building lifespan from the early construction phase to its demolition has more often than not been neglected. This work contributes to the existing knowledge on the role of EE in the lifetime primary energy consumption of typical Hellenic residential buildings representing different construction types and vintages. Cradle-to-gate embodied energy coefficients for the most common construction materials have been derived through data analysis from new field surveys and published data from local manufacturing facilities in Greece and compared against international data bases using the Simapro LCA software. Complementary data from the Ecoinvent LCI database have been used where necessary. Practical EE intensities for the building envelope and the share of EE in the whole lifetime energy consumption have been derived for residential building types, taking into account common renovation measures.

1. Introduction

In the frame of the global efforts for sustainability and environmental protection through the abatement of carbon emissions various European and national policies focus on improving the energy performance of buildings that represent 39.2\% of the total final energy consumption in the European Union and 37.9\% in Greece [1]. Residential buildings are at the center stage since they dominate the building sector and play a significant role in the energy and environmental footprint of buildings.

Current research efforts and policies are mainly focused on the effectiveness of strategies to minimize the energy demand towards nearly zero energy buildings (nZEB) by adopting more stringent building requirements and appropriate technologies for the new constructions as well as for the renovation of the aging building stock. Regulations for the energy efficiency of buildings focus on the energy and the emissions related to the operating phase of the building’s life cycle. Energy related key performance indicators are usually limited to the primary or final energy use intensities (EUI), i.e. operational energy use per unit floor area (GJ/m\textsuperscript{2}) and the resulting CO\textsubscript{2} emissions (kgCO\textsubscript{2}/m\textsuperscript{2}).

As the adoption and enforcement of more stringent regulations and standards drive EUIs of buildings to lower limits (i.e. higher energy performance buildings), more attention should be given to their total lifetime energy consumption. The total life cycle energy of a building includes the operational as well as the embodied energy. The operational energy (OE) is the energy used in...
buildings for space heating, domestic hot water preparation, cooling, lighting and operating other building appliances. The embodied energy (EE) includes the energy used for the acquisition of raw materials, processing, manufacturing and assembling building construction materials, equipment or system components at the factory gate (i.e. cradle-to-gate). The boundaries of the analysis can be extended to include the energy used for transportation to the building site (i.e. cradle-to-site), demolition, recycling and final disposal (i.e. cradle-to-grave). The recurrent embodied energy in buildings represents the energy consumed to maintain, repair, restore, refurbish or replace materials, components or systems during the life of the building. The EE in a building may represent 15-30% of its lifetime energy consumption [2-3] and it could exceed 50% in the case of high performance and nZEBs [4-6].

Current available EE data and international databases may exhibit variability because of inconsistent methodologies that are used to determine the embodied energy of building materials [7]. The trans-national variations in the availability of in-land resources, extraction and manufacturing practices as well as fuel mixes involved in the production of construction materials are some of the reasons why existing EE databases suffer from problems of incomparability and limited applicability.

In Greece, there is limited work on life cycle assessment about the embodied energy of Hellenic building construction materials. Some studies have focused on common building materials and analyze the life cycle stages of brick production, the constituent materials and the energy consumed in each life cycle phase [8] evaluating the environmental performance of cement and concrete in Greece [9]. Representative field studies in two local manufacturers in Greece have been performed to collect data on annual production and energy use to derive indicative cradle-to-gate EE coefficients for ready-mix concrete and clay bricks [10].

This paper aims at contributing to the existing knowledge by providing EE coefficients of construction materials used in the Hellenic residential building sector, as they were derived through field studies and analysis of data from local manufacturing facilities. Additionally, in an effort to get better insight of the embodied energy in Hellenic building structures, four representative building types of single family houses were selected and the relative contribution of the EE in their total lifetime energy consumption was assessed. Finally, the impact of EE on some popular measures for the energy retrofit in Hellenic residential buildings was investigated.

2. Methodology

A literature review of national and international published data provided a comprehensive overview of available information for different materials used in the construction of Hellenic buildings. In an effort to enhance the knowledge base on the energy embodied in Hellenic constructions, field studies in manufacturing facilities were carried out. The cradle-to-gate EE of commonly used building materials was determined using the SimaPro LCA software package [11] and compared against data from the well-known EcoInvent LCI database [12].

The objective of the present work was two-fold: first, to calculate the share of the EE to the total primary energy consumption over the lifetime of representative Hellenic residential buildings and second, to assess the impact of the embodied energy associated with popular energy conservation measures (ECMs) on the resulting operational energy savings.

Representative Hellenic residential buildings were used as case studies and a simple bottom-up process analysis was carried out in order to identify and quantify the main types of construction materials. Material masses were then associated with their embodied energy coefficients (MJ/kg). The embodied energy, initial and recurrent, of the case studied buildings was calculated, using the embodied energy coefficients derived from the field studies and complementary data from the EcoInvent LCI database where necessary. The operational primary energy consumption of the buildings was calculated using the national software for building labelling TEE-KENAK in order to derive the share of total embodied energy to the lifetime operational energy. Finally, the primary energy savings from the application of commonly adopted ECMs were compared against the associated EE in order to investigate the impact of the latter on their overall effectiveness.
2.1. Field surveys
In order to derive embodied energy coefficients reflecting the production of the common construction materials met in the Hellenic building stock, a number of field surveys were carried out in selected local manufacturing facilities for the production of bricks, mortar, mosaic, plasters, concrete, cement. Information regarding the types and quantities of raw material, manufacturing processes and related energy consumption per stage of production were collected through questionnaires, on-site visits, meetings with company representatives, as well as published documents and Environmental Product Declarations (EPDs). Furthermore, an extensive literature survey was carried out to gather relevant information from previously published works. The work to collect national data is very time consuming and stumbled on the reluctance of large manufacturers to release relevant data as they perceive it as “proprietary” information, while also revealing the gap of readily available voluntary EPDs. This is a hurdle that needs to be taken into account while developing mandates to perform EE analysis.

Using the collected data as input to the SimaPro LCA software, cradle-to-gate embodied energy coefficients were derived for a total of eleven major construction materials. The primary embodied energy was calculated using the Hellenic electricity fuel mix of 2016 (coal 33.16%, oil 10.83%, natural gas 26.6%, renewables 29.01% and wastes (non-renewable) 0.40%). The calculations were repeated with input data from EcoInvent LCI representing manufacturing processes and electricity fuel mixes in Europe.

Table 1 summarizes the cradle-to-gate embodied energy coefficients per unit mass, as they were derived by SimaPro software using data from the field surveys and publicly available Hellenic data, complemented by EcoInvent where necessary. The most EE intensive material was found to be aluminium, followed by stonewool and steel rebar. Concrete was among the least intensive ones.

| Materials            | Embodied Energy (MJ/kg) | Sources                                           |
|----------------------|-------------------------|---------------------------------------------------|
| Aluminium            | 209.2                   | Published Hellenic data [13] & EcoInvent          |
| Stonewool            | 37.8                    | Published Hellenic data [14,15] & EcoInvent       |
| Steel rebar          | 15.72                   | Published Hellenic data [16] & EcoInvent          |
| Roof (clay) tiles    | 3.38                    | Field survey                                      |
| Bricks               | 2.33                    | Field survey                                      |
| Mortar               | 0.78                    | Field survey                                      |
| Mosaic               | 0.74                    | Field survey & EcoInvent                          |
| Plasters             | 0.72                    | Field survey                                      |
| Concrete             | 0.51                    | Field survey                                      |
| Cement cast plaster floor | 0.39               | Field survey                                      |
| Lean concrete        | 0.32                    | Field survey & EcoInvent                          |

The derived primary EE coefficients are within the range of previously published cradle-to-gate values included in European databases for UK, North and Central Europe and France, reported in [7]. Comparison with the corresponding EE coefficients derived using the EcoInvent database revealed differences, the most significant of which refer to plaster, stonewool, aluminium and steel rebar. The closest agreement between the two datasets was found for concrete. The observed differences can be attributed to the various energy fuel mixes for the production of electricity associated with the production stages of construction materials in EcoInvent LCI as well as to the manufacturing processes that may vary among countries. Specifically, the production of plaster in Greece is based on the use of limestone sand, whereas, silica sand is used in the process described in EcoInvent LCI, the
production of which requires large amounts of energy. Similarly, steel rebar in Greece is produced by 100% scrap, whereas in the process described in EcoInvent LCI a significant portion (84%) is based on the use of raw steel. Finally, the main difference in the calculation of the EE of aluminium is attributed to the fact that the electricity mix associated with its production in EcoInvent LCI involves a high share of renewables (mainly hydro).

In the absence of published Hellenic data on other building materials, the SimaPro software was used in order to complement the Hellenic set of EE coefficients using data and processes described in EcoInvent LCI combined with the Hellenic fuel mix for electricity where necessary. The final set of Hellenic material EE coefficients included twenty eight entries covering a representative range of materials used in the building envelope and a limited number of electromechanical installations.

2.2. Case studies

Four representative Hellenic single family houses were used as case studies in order to identify the main types of construction materials and then quantify the corresponding material masses. The selected buildings are all located in climate zone B and they represent different types of construction according to their vintage: pre-1980 (‘old’ buildings before the first building thermal insulation regulation (HBTR) was introduced in Greece, so the buildings are considered without thermal insulation), 1981-2000 (considered partially or insufficiently insulated), 2001-2010 (thermally insulated according to HBTR) and post-2011 (considered up to the 2010 national regulation on the energy performance of buildings (KENAK regulation). The main characteristics and construction details of the case studies are summarized in Table 2. The floor areas refer to the heated (living) areas and they are used for normalizing the primary operational and embodied energy. The energy-class label according to the calculations using TEE-KENAK software is also included for the existing condition of the buildings, along with the calculated annual primary energy consumption. Average climatic data for climate zone B were used.

Table 2. Characteristics of the four case studied buildings (CS1-4).

| Age band   | Description                        | Floor area (m²) | Load bearing structure          | Walls                        | Floors                                      | Roof                  | Windows                                      | Heating system | Cooling system |
|------------|------------------------------------|-----------------|---------------------------------|-----------------------------|---------------------------------------------|-----------------------|---------------------------------------------|---------------|---------------|
| CS1        | pre-1980, single floor, sitting on | 80              | Reinforced concrete             | Clay bricks (67.83m²)       | Reinforced concrete, ceramic tiles (66m²) and wood (32m²). In contact with the ground | Tilted, reinforced concrete and clay tiles | Single glazings and wooden frames (19m²) | Oil boiler (0.79) | Split units (1.7) |
| CS2        | 1981-2000, single floor with pilotis, partly insulated according to HBTR | 130             | Reinforced concrete             | Clay bricks, 5cm polystyrene foam (74.5 m²) | Reinforced concrete, ceramic tiles (65m²) and wood (65m²). In contact with outside air (pilotis) | Flat, reinforced concrete, with 6cm extended polystyrene | Double glazings (12mm air gap) and aluminium frames (26.5m²) | Oil boiler (0.82) | Split units (1.7) |
| CS3        | 2001-2010, 2-floor, with underground heated space, fully insulated according to HBTR | 150             | Reinforced concrete, with 5 cm extended polystyrene | Clay bricks with 5cm extruded polystyrene (166m²) | Reinforced concrete, ceramic tiles (40m²) and wood (40m²), 4cm extruded polystyrene. In contact with unheated space | Tilted, reinforced concrete, clay tiles and 6cm extended polystyrene | Double glazings (12mm air gap) and aluminium frames with thermal brakes (43m²) | Oil boiler (0.86) | Split units (1.7) |
| CS4        | Post-2011, 2-floor, with underground unheated floor, insulated according to KENAK | 155             | Reinforced concrete, with 6 cm extended polystyrene | Clay bricks with 6cm extruded polystyrene (169m²) | Reinforced concrete, ceramic tiles (42m²) and wood (42m²), 5cm extruded polystyrene. In contact with unheated space | Flat, reinforced concrete, 6cm extended polystyrene | Double glazings (12mm air gap), low-e and aluminium frames with thermal brakes (40 m²) | Oil boiler (0.89) | Heat pump (2.7), movable shading |
According to the national regulation, the calculation method for residential buildings accounts for an 18-hr operation of space heating, space cooling and domestic hot water (DHW). Other energy end-uses like lighting (only considered for non-residential buildings), cooking, white appliances and other plug-loads, are not taken in to account.

3. Embodied energy
In an effort to assess the relative impact of the different construction materials on the overall EE of the buildings, a detailed calculation of their respective quantities in each of the case studies was carried out. The calculated quantities were then associated with the corresponding material EE coefficients in order to derive the total initial EE of each building. Calculations were carried out using both the Hellenic and the EcoInvent sets of material EE coefficients, in an effort to investigate the impact of using the different databases on the results. In order to account for the embodied energy associated with transportation from the factory gate to the construction site, an average distance of 100 km was assumed, with the exception of concrete where this distance was reduced to 40 km. Figure 1 depicts the resulting cradle-to-site embodied energy intensities (EEI) for the four case studies. The calculated initial EEI using the Hellenic set of material EE coefficients ranged from 3.2 GJ/m² to 7.1 GJ/m² with an average of 5.6 GJ/m², while the EcoInvent results were found to be 15% higher on average. The calculated EEIs using the Hellenic set of material EE coefficients are within the range of other findings reported in the literature, e.g. 5.51 GJ/m² in [7], 6.23 GJ/m² in [10] and 1-8.35 GJ/m² in [6].

3.1. The role of materials
The EEI of a building depends on the share of the different materials in the total building mass. In Hellenic residential buildings concrete is the dominant construction material followed by bricks and steel rebar. Figure 2 depicts the mass and embodied energy distribution for the different construction materials.
materials in the case studied buildings. The average share of concrete and bricks in the overall building mass was found to be 71% and 11% respectively. Plasters (cement cast, base plaster and mortar) and steel rebar averaged 8% and 2.6% of the building mass respectively. The share of thermal insulation material, where present, was significantly smaller (0.13%).

![Figure 2. Building material mass (left) and embodied energy (right) distribution in the four case studies.](image)

Due to the differences in the embodied energy of each material, their ranking in the share of the total EE in the case studied buildings follows a different pattern. Concrete is the main contributor representing 28% of the total EE on average, while steel rebar appears to be the second major contributor representing an average of 26%. Despite their minor share in the total mass of the studied buildings, thermal insulation and aluminium contribute to the total EE of the more recent constructions by up to 10% each.

According to their material composition and their share in the total building mass, structural elements represent different shares of the total embodied energy. Overall, the load bearing structure represents the highest material quantities and the main component of the total embodied energy of the studied buildings. Although windows (frame and glazing) represent a small percentage of the total building mass, their share in the EE of buildings CS2-CS4 is close to 10%, due to the use of aluminium in the window frames.

3.2. The share of EE in lifetime energy consumption

The building lifetime was assumed at 80 years in order to assess the share of embodied energy in the total energy consumption of the case studied buildings throughout their lifetime. The total lifetime EE of the buildings was calculated taking into account both initial and recurrent EE (Figure 3). The recurrent embodied energy in buildings represents the energy consumed to maintain, repair, restore, refurbish or replace materials, components or systems during the life of the building. The recurrent EE was calculated by accounting for standard maintenance with cycles varying according to the service life of materials (Table 3), as indicated in [17]. The recurrent EE of the case studied buildings was found to be equal to 40% of the initial embodied energy. The share of the total embodied energy (initial and recurrent) to the total primary energy consumption (total embodied and operational) of the
case studied buildings ranged from 3% to 27%, increasing as the building’s energy performance reaches higher levels.

Table 3. Service life of common building elements and products.

| Material               | Service life (y) |
|------------------------|------------------|
| Boiler                 | 20               |
| Paint                  | 10               |
| Plastering (outdoor)   | 50               |
| Glass                  | 30               |
| Window frames          | 30               |
| Mosaic                 | 30               |
| Timber                 | 55               |
| Laminated floor        | 35               |
| Roof tiles (clay)      | 30               |
| Ceramic tiles          | 30               |
| Insulation (external)  | 50               |
| Exterior door          | 40               |

Figure 3. Total primary energy consumption breakdown over a lifetime period of 80 years.

This study is restricted to the EE of the building envelope only; the calculated shares would be higher, if the EE of electromechanical systems in the buildings had been included. Moreover, the recurrent energy was calculated considering the replacement of materials with new ones of the same standard. In reality, replacement of deteriorated building materials (ie insulation) and products (windows, boiler) would involve an upgrade towards higher standards in line with regulation mandates and market trends, which would improve the energy performance of the buildings reducing the operational energy. Consequently, the embodied energy share would be increased.

4. Impact of EE on the effectiveness of ECMs

Existing buildings have a high potential for significant energy savings by implementing different energy conservation measures, especially for space heating and DHW. In Greece, the replacement of windows is the most common ECM for all types of Hellenic residential buildings [18]. Although this is not the most effective measure for maximizing energy savings, the additional side benefits (e.g. improved indoor thermal conditions, sound proofing, aesthetics and security) and the fact that this measure is easy to implement, it has clearly become an action of choice for most homeowners. Other popular measures include the installation of solar collectors for DHW and the addition of roof thermal insulation in single family houses, averaging 41% primary energy savings.

Depending on the annual operational energy savings, it may take several years to recover the embodied energy associated with materials of a specific measure. In order to investigate the impact of embodied energy on the actual effectiveness of different energy retrofit measures, various ECMs were assessed for the case studied buildings CS1, CS2 and CS3. These involved single interventions on the envelope (i.e addition of thermal insulation on the roof and walls, replacement of windows) and systems (replacement of boiler, addition of solar collectors for domestic hot water heating) and a package including a combination of the afore-mentioned interventions. All ECMs involved upgrade of the building components involved to the standard required by 2017 national KENAK regulation. The ECM that refers to the addition of thermal insulation was not assessed for building CS3, since the cost for upgrading the insulation level of this building (fully insulated according to HBTIR) is not considered a cost-effective priority at this stage. For each ECM the associated increase in the EEI of the building was compared to the respective decrease in its operational primary energy use intensity (EUI) to derive the time period required for the impact of the EE to be outweighed by the anticipated
energy savings. Figure 4 illustrates the recovery periods calculated for the assessed measures in the four case studied buildings.

The recovery period for most ECMs was found to be higher for the most recently constructed building (CS3) due to lower energy savings. The longest recovery periods were calculated for the ECMs involving a replacement of openings and ranged from 2.6 to 6 years. Replacing the single glazed, wooden frame openings of CS1 building with double glazed, coated ones with aluminium frames and thermal brakes improved its operational energy by 12%, which stands for a reduction of 0.249 GJ/m$^2$. The corresponding EEI increase was 0.641 GJ/m$^2$, which represents 18% of the initial EEI and was found to be compensated by the resulting operational energy savings in 2.6 years. The same measure when applied to building CS3 resulted in reducing its operational energy by 9%, standing for 0.092 GJ/m$^2$. This significantly smaller reduction compared to that achieved in CS1 is due to the fact that building CS3, included double glazed windows with aluminium frames, so the measure was less effective than in the case of building CS1. The corresponding EEI was increased by 0.558 GJ/m$^2$, representing an increase by 8% which was found to be compensated by the operational savings in 6 years.

Figure 4. Embodied energy impact recovery periods for ECMs applied in the three case studied buildings.

5. Conclusions
A realistic assessment of the potential for energy consumption and emissions reduction in the building sector is progressively performed following a life cycle approach. However, the contribution of the embodied energy associated with the building lifespan from the early construction phase to its demolition has more often than not been neglected.

A bottom-up approach was used to calculate the embodied energy associated with the main building construction materials for four representative types of single family houses in the Hellenic building stock. In order to overcome the scarcity of comprehensive national data regarding the EE of construction materials, as a first approximation, a list of cradle-to-gate EE coefficients was derived including a total of 11 construction materials used in Hellenic buildings based on data from field surveys in local manufacturing facilities, published literature and publicly available EPDs. The Hellenic list of material EE coefficients includes a total of 11 entries, which have been complemented with data for 15 more construction materials from the EcoInvent database adapted to reflect the Hellenic manufacturing processes and fuel mixes involved.
Considering the building envelope materials, the EEI of the case studied buildings ranged from 3.2 GJ/m$^2$ to 7.1 GJ/m$^2$ with an average of 5.6 GJ/m$^2$. While the EUIs decrease for buildings that comply with the new standards, the EEI increases from the lower to the higher performing buildings. Accounting for the embodied energy of implemented energy conservation measures in existing buildings the analysis revealed that they outweigh some of the operational energy savings with a recovery time in the range of 1 to 6 years.

Compared to embodied energy, operational energy constitutes a relatively larger proportion of a building’s total life cycle energy. However, the significance of embodied energy and its relative proportion of total energy are growing with the emergence of more energy efficient buildings. In the present study, the share of EE in the total primary energy over a lifetime period of 80 years was found to range from 2.6% for the worst performing building (CS1) to 26.5% for the best performing building (CS4).

Accordingly, the importance of embodied energy and its relative proportion to the total life cycle energy use in the buildings sector will become important and progressively put more emphasis on the proper selection of building materials and systems that have a low EE. The existing international tools and databases that facilitate the calculation and assessment of a building’s EE should be further enhanced with nationally representative values. Given that this is a time consuming process, the present work enhanced the existing knowledge by providing new field data that was used to derive practical benchmarks for the EEI to be used for the initial assessment of representative residential buildings and common ECMs. The near term plan is to enhance the work with the development of similar EEIs as benchmarks for the representative Hellenic residential and non-residential buildings, and progressively expand the work for the electromechanical installations. The goal is to complement the corresponding indicators for operational energy use intensities and populate the matrix of representative Hellenic buildings that facilitate the decision making process at the early design phases for accessing operational energy savings.

Acknowledgments
Authors acknowledge the support of this work by the project “THESPIA II – Foundations of synergistic and integrated management methodologies and tools for monitoring and forecasting of environmental issues and pressures” (MIS 5002517) which is implemented under the action “Reinforcement of the Research and Innovation Infrastructure”, funded by the Operational Programme “Competitiveness, Entrepreneurship and Innovation” (NSRF 2014 – 2020) and co-funded by Greece and the European Union (European Regional Development Fund).

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