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Unveiling the contribution of building's embodied energy to global CO_2 emissions

The case of residential buildings in Berlin

Kopernikus Projects ENavi

Working Package 4 | Task 7 "Technical-systemic analysis with a focus on energy efficiency in buildings"

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KOPERNIKUS PROJEKTE
Die Zukunft unserer Energie

GEFÖRDERT VOM
Bundesministerium für Bildung und Forschung

Forschungsinitiative Kopernikus

The Federal Ministry of Education and Research (BMBF) has allocated a total of EUR 400 million to fund the Kopernikus program until 2025. The objective of the program is to develop innovative technological and economic solutions that can facilitate the transition to a more sustainable energy system. Over a period of 10 years, more than 230 partners from science, business and civil society will conduct research in four subject areas: “New Network Structures”, “Storage of Renewable Energies”, “Reorientation of Industrial Processes” and “System Integration”. Researchers are adopting a holistic approach to these four subprojects in order to examine specific issues relevant to the individuals and institutions that play key roles in energy generation, transmission, supply, and distribution. The program's 10-year lifespan ensures that the initiative will include a long-term interchange between theory and practice.

System integration: ENavi

As a participant in the “ENavi” subproject, IKEM is partnering with roughly 90 institutions from the fields of science, business, and law to develop a navigation system that promotes the transition to sustainable energy. Because system integration is vital to the success of comprehensive energy reforms, the program partners' integrative approach includes research on heat, gas, and fuel use. IKEM plays a key role in ensuring that the findings from theoretical analyses can be applied in practice. From the outset, field tests are conducted to assess the concrete technical, economic, and legal implications of the energy transition. Test results can then be applied to other regions. Program partners intend to expand the initiative to include research on 50 municipally owned power generation and electricity distribution companies, or Stadtwerke.

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Introduction

The report in the context of ENavi

The German energy transition presents one of the greatest challenges for all sectors of the economy. The building sector individually represents one of the largest consumers in the energy balance. It is therefore necessary to make every effort to increase the energy efficiency of the sector and significantly reduce energy consumption in buildings throughout their entire life cycle. Thus, in a previous work within the Kopernikus ENavi Project (see Mercado 2018) it is discussed that the total energy consumption within the useful life of buildings contemplates the energy consumption of buildings the different stages of their useful life; the main phases are: design, product manufacturing, construction, use or operation, end of life.

The operating phase of buildings has significantly higher energy consumption than the other phases. Therefore, to date efforts have been made to improve energy efficiency during the use of buildings. Thus, thanks to technological development and changes in building code regulations, mainly focused on the building's thermal envelope and heating systems, energy efficiency in buildings has been significantly improved over the past 40 years. However, the reduction of energy incorporated in buildings, whether in the construction process or in the manufacture of building materials, has not advanced significantly. The barriers to this, according to recent literature, are the absence of regulations, the lack of comparable methodologies, and limited access to data, among others.

From a climate protection perspective, the process of transformation to a climate-neutral built environment implies a fundamental change of direction and a holistic approach that considers the impacts generated by all activities in the sector. In order to do this, beyond a focus on energy saving and efficiency, we must also think about the climate and environmental impacts generated throughout the life cycle of the built environment. Thus, beyond the efforts mentioned above, the focus should be on energy analysis in the cycle of materials and the sustainable use of raw materials and resources.

Thanks to a close relationship between scientific research and professional practice, which is enabled within the Kopernikus ENavi framework, IKEM contributed to the research focussed in the reduction of CO_2 emissions in the construction sector by analysing a real example in the local construction industry. Thus, thanks to the detailed information provided by GESOBAU, also a project partner in the Kopernikus ENavi framework, IKEM analysed the embodied energy of building materials used in Berlin`s housing stock.

The main aim of the research is to explore the potential contribution of lower-embodied energy construction materials to reducing the sector's CO_2 emissions already from the design and construction stage of buildings at an earlier stage of the process.

The research contributes to the built environment research in German context, focusing mainly on the local implementation of EU regulations, namely regarding the circular economy (such as the so-called 'Circular Economy Package') and the building energy performance (i.e. EU-EPB 2018), which must be implemented gradually in Germany.

Background and motivation: energy consumption in the construction sector

Motivated by the first oil-crisis in 1973, which had a significant impact on the energy sector among others, most countries have implemented different energy efficiency and energy saving measures in the building sector. The later has enabled a decrease in buildings' operational energy consumption.

According to UNEP-SBCI (2009) the building sector is responsible for 40% of global energy consumption and 30% of anthropogenic greenhouse gas (GHG) emissions. The EU building sector shows a similar trend where the sector is widely appointed as a primary source of GHG emissions, contributing directly to climate change. Previous research (see Mandley et al. 2015) estimate the sector to account for approximately 40% of primary energy use and 50% of extracted materials within the EU. Therefore, the EU has implemented the Energy Performance of Buildings Directive 2010/31/EU (EU–EPB 2010) which requires efficiency improvements to be implemented in all new EU buildings, with a requirement that from 2020 all new buildings constructed with higher standards for enabling 'nearly energy zero' buildings. According to the German Federal Ministry for Economic Affairs and Energy (*Bundesministeriums für Wirtschaft und Energie* or BMWi), In 2010, almost 40 % of final energy consumption in Germany is accounted for by the construction sector, which shows a similar trend as the EU. The foregoing reflects a significant potential for the implementation of measures to reduce the sector's energy consumption and GHG emissions and to improve its energy efficiency in the past decades. To date, regulations (both European and national) have focused mainly on reducing energy consumption in the use phase of buildings, leaving open the opportunity to intervene in the other phases in order to realise the sleeping potential.

It is therefore relevant keeping in mind that building's energy performance includes operating energy and the embodied energy. The sum of all energy embedded in products and processes used in constructing a building is known as embodied energy. Unlike operating energy, measuring embodied energy is a complex, unstandardized, and very data-intensive process. The literature review on embodied energy research highlights three major issues: 1) there is little agreement on the definition of embodied energy; 2) existing embodied energy data suffers from variation and are regarded as incomplete and not too specific; 3) there are various methods for calculating embodied energy with varying levels of completeness and accuracy. Therefore, the research seeks to illuminate the three aspects mentioned above through the analysis of a case study of an existing residential building in Berlin

I. Research Design and Methods

1. Research Approach and Aims

The research involves the close interaction between scientific research and practitioners from the building sector to explore the contribution of building's embodied energy to global greenhouse gas emissions by analysing the case study of Berlin's housing sector while contributing to the achievement of ambitious national climate goals. From this stance, in order to meet the Energy Performance of Buildings Directive 2018/844/EU (EU–EPB 2018) the embodied energy of a building, when taking a full life-cycle perspective, is gaining importance and will become a more dominant issue to tackle when striving for sector-wide reduction in the near future. Therefore, the investigation provides relevant elements for compliance with European and national regulations.

The scientific work focuses mainly on two aspects: 1) the detailed review of current concepts and methodologies for the assessment of residential buildings embodied energy; and 2) embodied energy calculations based on the data provided by the case study. On the other hand, the practitioner's contribution was significant since it provided detailed information for the construction of the case study. The overall research objective is to explore the contributions building's embodied energy to global CO_2 emissions, by considering specifically 1) the materials used for its construction, taking into account their characteristics and precise amounts; and 2) a calculation methodology that fits the available information. The specific aims of the research are:

- To undertake a comprehensive analysis of the state of the arts of definitions and methods for estimating building's embodied energy.
- To estimate the embodied energy of a new construction multi-family building from Berlin's housing sector.
- To explore alternative embodied energy scenarios by selecting materials with higher and lower embodied energy than the case study.

Scope and Limitations

The research was solely focused on building's embodied energy and did not address any issue related to building's operating energy, mainly because the case study selected for analysis is a new building that was not yet occupied; therefore, data on energy consumption in the operating phase were not available. As mentioned in the literature review, the selection of a material based on its low embodied energy could affect a building's operating energy. Any such analysis, nonetheless, was out of the scope of this research.

2. The Case Study

The case study is a newly constructed multi-family three storeys housing complex. The complex is in the district of Pankow, which is located northeast of the city of Berlin in a predominantly residential area. Table 1 describes the main characteristics of the housing complex, while Figure 1 show an aerial view of the complex. The main features of the housing complex are detailed below.

General information

- The buildings will be constructed as solid structures (reinforced concrete structures and masonry structures). House 1 and house 3 have a partial basement.
- In the 1st basement of these buildings there are only cellars and technical rooms.
- The ceilings are constructed as massive ceilings in reinforced concrete with a thickness of 20 cm (floor ceiling dimensioning according to statics and sound insulation). The floor slabs are given a floating screed.
- The walls to the staircase as well as the elevator walls are designed as reinforced concrete walls with a thickness of 22 to 30 cm. Apartment partition walls are designed either as masonry walls or reinforced concrete walls according to static requirements.
- Non-load-bearing partition walls are constructed as lightweight partition walls (stud frame construction) according to the specifications of the client / construction management.
- The facades with window openings are intended as load-bearing brickwork facades.

Figure 1 Aerial view of the housing building complex.

Source: GESOBAU

As mentioned in the above sections, the information for building up the case study was provided by GESOBAU, a project partner within the Kopernikus ENavi project. The case study consists of a residential building project. The housing complex consists of 4 apartment-blocks in three different typologies. The predominant types of apartments are of 2 and 4 rooms, although in the whole building complex there are also apartments of 1.5, 3, and 5 rooms; the average useful area of the apartments is 78 m^2 (Min.: 1.5 rooms: 40 m^2; Max.: 5 rooms: 110 m^2) as described in the *Table 1* below.

Table 1 Case Study - Building Typologies and Key Features

	House 1	House 2.1 & 2.2	House 3
Areas to be developed [m²]	ca. 600	ca. 300	ca. 300
Apartment type [# rooms]	1,5 | 2 | 4	2 | 3 | 4 | 5	2 | 3 | 4 | 5
Average apartment area [m²]	70,03	78,25	80,25
Net area [m²]	1929,83	916,76	702,66
Heated building volume [m³]	6.913,35	3.466,98	2.547,10
Heated air volume [m³]	5.530,68	2.773,58	2.037,68
Envelope areas [m²]	2.897,34	1.489,20	1.337,44
Window areas [m²]	360,58	220,14	157,42
Useable area [m²]	2.212,27	1.109,43	815,07
Primary energy demand [kWh/(m²a)]	39,96	42,13	45,81
Transmission heat loss [W/(m²K)]	0,39	0,41	0,38

Source: Own elaboration based on GESOBAU

The values for primary energy demand and heat loss through transmission comply with the EnEV 2016 [1] standard; the average values are 42, 13 kWh/(m²a) and 0.39 W/(m²K) respectively.

3. Research Methods

A four-step (bottom-up) process analysis was implemented. Accordingly, building elements were selected in the first step, followed by a mass analysis, a life cycle analysis, and a scenario analysis, as described below.

a) Methodological Steps

Step 1 – Selection of building elements: In the first step, structural elements and the thermal envelope of the building were selected; moreover, the existing construction material of each building element were identified based on the information provided. The building elements selected were the following:

- Masonry (sand-lime brick)
- Concrete (C20/25 and C25/30)
- Reinforcement steel
- Insulation (XPS and rock wool)
- Doors (metal)

Step 2 – Mass analysis: For each material recorded in the previous step, its mass was calculated. A quantity survey was conducted for the GESOBAU buildings. The required data were extracted from the final building drawings and the information provided by GESOBAU.

Step 3 – Life cycle analysis: A set of indicators were calculated based on the mass values obtained in the previous step and the data provided by the ÖKOBAUDAT Platform. The section *Selected Indicators from ÖKOBAUDAT* provides a detailed overview on the selected indicators for the calculations.

Step 4 – Scenario analysis: The analysis carried out in the previous steps provided the embodied energy values of building components/materials under the current construction conditions; namely,

[1] The EnEV (short for *Energieeinsparverordnung*) is the German Energy Saving Ordinance; it describes the minimum requirements regarding energy use of new and renovated buildings. Since 1 January 2016, the EnEV has required a higher energy standard for newly planned and built residential and non-residential buildings (source: https://enev-online.de/index.htm).

a *'business as usual'* (or BAU) scenario that reflects the current state of affairs in the construction industry in Berlin. Based on the BAU-scenario, two more scenarios were calculated; namely, a *'lower embodied energy'* (or LEE) and a *'higher embodied energy'* (or HEE) scenarios.

b) Selected Indicators from ÖKOBAUDAT

The ÖKOBAUDAT Platform[2] was used to gather data sets that contain specific information about energy and emissions that are linked to the life cycle of the components/materials. As not every material was listed in the exact GESOBAU-version, comparable components were selected (e.g. instead of GESOBAU MW KS-Planstein it was used sand-lime brick). Data was collected for life cycle phases A1 to A3 since the ÖKOBAUDAT does not provide comprehensive information about the phases A to D for all materials. The later improves transparency and enables the direct comparison of the embodied energy of components and materials among themselves. In order to compare the selected building components and materials, the following indicators were selected:

Primary Energy Renewable -Total (PERT)

This indicator sums up the primary energy consumed from renewable productions. This indicator is not decisive, as it does not provide information about the affect onto the climate change. However, it indicates reasons for relatively high or low values of the following indicator.

Primary Energy Non-Renewable – Total (PENRT)

This indicator sums up the primary energy consumed from non-renewable productions. This indicator is very decisive, as it correlates with the emitted greenhouse gas emissions. Therefore, it stands for the embodied energy and was used for the assessment of the sustainability. The mass analysis and specific information on embodied energy then enabled the linkage of both data sources. The results are absolute numbers caused by the whole quantity of the above-mentioned building components/materials.

[2] The ÖKOBAUDAT platform, is an initiative of the German Federal Ministry of the Interior, Building and Home Affairs (*Bundesministerium des Innern, für Bau und Heimat* or BMI). It provides all stakeholders with a standardized database for the life cycle assessment of buildings. At the center of the platform is the online database with life cycle assessment data records on building materials, construction, transport, energy and disposal processes. Moreover, the data are subject to strict quality characteristics and can be used in the various building evaluation systems. For more information see: https://www.oekobaudat.de/

Global Warming Potential (GWP)

This indicator is a measure of how much heat a greenhouse gas traps in the atmosphere up to a specific time horizon, relative to carbon dioxide. This indicator was selected as it enables the conversion of greenhouse gases other than CO_2 to CO_2-equivalent. Furthermore, this indicator is commonly used to assess an effect on the climate change.

c) Comparative Analysis

As mentioned above, based on the BAU-scenario, two more scenarios were calculated; namely, a *'lower embodied energy'* (or LEE) and a *'higher embodied energy'* (or HEE) scenarios. The LEE-scenario was calculated considering materials that offer the same thermal performance but have a lower embodied energy content. On the other hand, the HEE-scenario was calculated with materials that offer the same characteristics but have a higher embodied energy content. The selection of the alternative materials was based on a comparison of specific values of the PENRT. However, concrete, reinforcement steel and XPS insulation were not changed since alternative materials (e.g. wood construction) comes with significantly different quantities and therefore does not allow a direct comparison of specific values. As a result, the following building elements were investigated with alternative materials in the three different scenarios:

- Masonry
- Doors
- Insulation

In order to ensure a comparability of different insulation materials, the U-values in the BAU-scenario for the insulation materials were used as a base characteristic. The thermal conductivity of alternative materials for the LEE and HEE scenarios were used to calculate the necessary thickness of alternative insulations based on the aspired U-value. As a result, the following scenarios were investigated, as described in the table below.

Table 2 Research Scenarios

Building Elements	LEE-Scenario	BAU-Scenario	HEE-Scenario
Masonry	Rammed clay wall	Sand-lime brick	Sand-lime brick
Insulation	Cork insulation	Rock wool	Wood fiber
Doors	Wood	Metal	Metal

Source. Own elaboration

The materials of the different scenarios meet the same requirements regarding to thermal permeability and statics. The decisive difference lies in the embodied energy of the materials used. Cork insulation, for example, contains a lot less embodied energy than rock wool even though both materials can fulfill the same requirements in terms of thermal permeability.

II. Building's Embodied Energy – Definitions and Methods

This section and the following subsections provide a summary of the literature review conducted as a methodological framework for research. The first and second sections provide a theoretical discussion of energy considerations in buildings in two main phases within their life cycle, i.e. embodied energy and operational energy; they also discuss the implications of CO2 emissions in both phases. The third section provides a review of the methods for the calculation of embodied energy found in the relevant literature.

1. Building's Embodied vs. Operative Energy

According to Crowther (1999) the construction and operation of buildings requires energy, and the production of that energy, depending on the energy sources, creates major environmental impacts through the generation of CO_2. While the switch over from energy sources (i.e. fossil fuels to renewable energy sources) may have a greater impact on the reduction of CO_2 emissions in the construction and operation of buildings, it is also relevant to seek the reduction of CO_2 emissions at all stages in the building sector.

While there has been much research into the possibilities of reducing operational energy consumption (see Crowther 1999, Ramesh et al. 2010, Cabeza et al. 2014), the research about reducing the energy required for the construction of buildings and for the manufacture of construction materials is rather scarce. A feasible explanation for such lack of interest in the research is that it has commonly been accepted that the operational energy of a building over its lifetime (depending on the building type and construction method) is greater than the energy required to construct the building and for manufacturing building materials and elements. Attention has therefore focused on the area where it was perceived that the greatest energy savings could be made (Crowther 1999). Moreover, most of the energy efficiency measures implemented in the building sector are closely related to the thermal performance of the building envelope, because of the higher energy demands generated by the heating, ventilation, and air conditioning systems in the buildings (see Mercado 2015).

Current research in the built environment suggest that the initial energy of building construction is much higher than previously thought and shows, therefore, an increased interest in considering the buildings life-cycle perspective. It now appears, therefore, that operational energy is not the only significant factor for reducing the to reduce the sector's energy consumption and CO_2 emissions. From this perspective, it is also relevant to consider how the useful life of buildings ends; that is, to consider how much energy is contained in the demolition of buildings and the recycling of materials in order to reinsert them in the production chain, as described in the Figure 2.

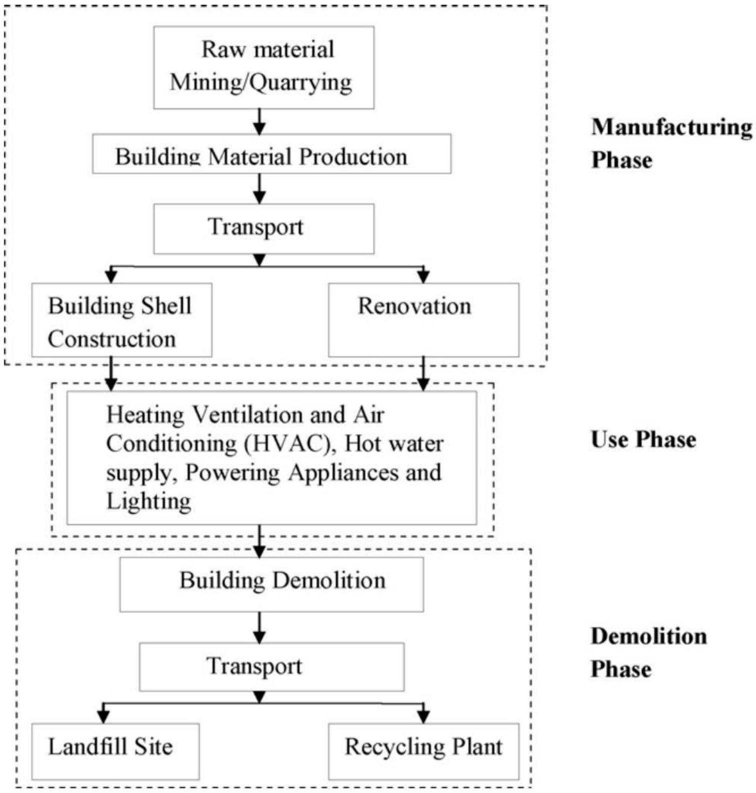

Figure 2 System Boundaries for the Life Cycle Energy Analysis

Source: Ramesh et al. (2010:1593)

Buildings consume energy directly or indirectly in all phases of their life cycle right from the cradle to the grave and there is interplay in the total life cycle energy (embodied, operating, and demolition energy); hence, they need to be analyzed from life cycle point of view (Ramesh et al. 2010, Dixit et al. 2010, Thomas et al. 2015). The table below provides a comprehensive overview about the above-mentioned interplay in each one of main phases.

Table 3 Phases of Energy Use

Phases of Energy Use	Description
Embodied energy	Energy content of all the materials used in the building and technical installations, and energy incurred at the time of new construction and renovation of the building.
Operating energy	Energy required for maintaining comfort conditions and day-to-day maintenance of the buildings. Energy for HVAC (heating, ventilation and air conditioning), domestic hot water, lighting, and for running appliances.
Demolition energy	Energy required at the end of the buildings' service life to demolish it and to transport the material to landfill sites and/or recycling plants.

Source: Own elaboration based on Ramesh et al. (2010), Dixit et al. 2010

According to Miller (2001), the term embodied energy is subject to various interpretations rendered by different authors and its published measurements are found to be quite unclear. The table below provides an overview on the most relevant definitions founded in the literature.

Table 4 Embodied Energy Definitions

Source	Year	Embodied Energy is …
Crowther	1999	… the total energy required in the creation of a building, including the direct energy used in the construction and assembly process, and the indirect energy, that is required to manufacture the materials and components of the buildings.
Treloar et al.	2001	… the energy required to provide a product (both directly and indirectly) through all processes upstream (i.e. traceable backwards from the finished product to consideration of raw materials)
Langston & Langston	2008	… the energy demanded by the construction plus all the necessary upstream processes for materials such as mining, refining, manufacturing, transportation, erection and the like.

Source: Own elaboration based on Surahman (2014:13)

As can be seen in the table above, definitions of embodied energy in the scientific literature have varied over time. Ding's work (2004:70), based on: Baird (1994), Edwards & Stewart (1994), Howard and Roberts (1995), Lawson (1996), and Cole & Kernan (1996), provides a more comprehensive definition, namely: "embodied energy comprises the energy consumed during the extraction and processing of raw materials, transportation of the original raw materials, manufacturing of building materials and components and energy use for various processes during the construction and demolition of the building".

2. Building Materials Embodied Energy

The energy analysis of in manufacturing process of building materials has been researched since the 1970s, owing to its larger share in the total life cycle energy. However, as mentioned in the previous sections, its relevance has been overlooked because the focus of research and regulatory implementation was absorbed on the operation stage of buildings. This scenario has changed significantly in the last decade due to the advent of energy efficient equipment and appliances, along with more advanced and effective insulation materials, the potential for curbing operating energy has increased and as a result, the current emphasis has shifted to include embodied energy in building materials.

The prevailing building system in the building sector plays a predominant role in the amount of energy needed to manufacture a unit of material or a building element. Thus, a traditional system, where most elements are manufactured in-situ, has a lower embodied energy than an industrial building system. In contrast, building off-site manufacturing shows a higher embodied energy. According to Ding

(2004) the production of building components off-site accounts for 75 percent the total energy embedded in buildings. Moreover, according to Langston & Langston (2008) and Sartori & Hestnes (2007), this share of energy is growing as a result of the increased use of the so called 'high energy intensive materials' in the construction industry. The Table 5 provide a clear overview regarding the differences between very high energy materials and low energy materials.

Table 5 Comparative energy requirements of building materials

Energy Intensity	Material		Primary energy requirement (GJ/ton)
Very high energy			
	Aluminium		200 - 250
	Plastics		50 - 100
	Copper		100 +
	Stainless steel		100 +
High energy			
	Steel		30 - 60
	Lead, zinc		25 +
	Glass		12 - 25
	Cement		5 - 8
	Plasterboard		8 - 10
Medium energy			
	Lime		3 - 5
	Clay bricks and tiles		2 - 7
	Gypsum plaster		1 - 4
	Concrete:		
		In situ	0.8 - 1.5
		Blocks	0.8 - 3.5
		Precast	1.5 - 8
		Sand-lime bricks	0.8 - 1.2
		Timber	0.1 - 5
Low energy			
	Sand, aggregate		<0.5
	Flyash, RHA, volcanic ash		<0.5
	Soil		<0.5

Source: Bending & Eden (1984) in Habitat (1991)

Beyond the primary energy requirements mentioned in the Table 5, the literature review accounts for other key factors that determine energy consumption in the construction materials manufacturing process. The **Error! Reference source not found.** presents key factors affecting the energy c onsumption of building materials during their life cycle.

Table 6 Key factors affecting the energy consumption of building materials

Main Factor	Description
Transport – logistics	The amount of energy and CO_2 spent in transporting building materials from production sites (countries) to construction sites. The economic and ecological impacts will depend on the distance that materials need to travel.
Origin of the raw material	A large amount of energy is used in manufacturing building materials; that is, in transforming raw material into building material. The use of recycled building materials could reduce the embodied energy in the building; e.g. the use of recycled metal makes considerable energy savings between the rates of 40% and 90% comparing the material produced from natural resources (Berge 2009).
Materials processing	Energy invested in processing construction materials, e.g. wood versus ultra-high-performance concrete. Thus, 'natural materials' have lower embodied energy than 'artificial materials' since these materials are manufactured with less energy and labor cost.
Level of industrialization and manpower	The intensity of energy consumption in the production of construction materials and buildings' components has increased dramatically with industrialization; e.g., cement manufacturing technology, using the shaft furnaces instead of the conventional rotary furnaces makes energy saving between 10% and 40%. Similarly, the use of arc furnace instead of rotary furnace in steel industry makes about 50% energy saving (Berge 2009). Using highly qualified manpower in manufacturing materials reduces the processes based upon industry, and accordingly decreases the energy consumption.
Energy resources used	The use of renewable energy resources as a primary energy in the manufacturing process. For example, the adobe brick is dried using solar energy after it is molded.
Durability of materials	Use of durable materials in the buildings makes them more resistant and long-lasting against various factors. This reduces maintenance and component replacement requirements.

Source: Own elaboration based on Yüksek (2015) and Berge (2009)

The above factors account for the need for appropriate methodologies for the calculation of embodied energy in building materials. Many of these factors account for the importance of the local context in energy analysis. Many of the decisions of the local construction industry, as well as the predominant building system among others, can significantly affect the results of the analysis. Likewise, the way in which the useful life of buildings comes to an end within the local industry significantly affects the energy consumption of the sector.

3. Methods for Embodied Energy Assessment

As mentioned in the introduction, a systematic review of secondary sources of information was conducted for analysing current literature in the field of embodied energy in the built environment research and the methods used in the research field. This section and subsections below present an overview on life cycle assessment (LCA), as the most relevant methods found in the literature for assessing the embodied energy of buildings.

LCA has been used in the building sector since 1990 (see Ortiz et al. 2009, Fava 2006, Taborianski 2004 cited in Cabeza 2014:396) and has also been used to assess product development processes from cradle to grave for many years (see Sharma et al 2011, Singh et al. 2011, Ramesh et al. 2010, Hertwich 2005, Zabalza et al. 2009). With the current push toward sustainable construction and towards achieving circularity in the construction industry (see Mercado 2018), LCA has gained importance as an objective method to evaluate the environmental impact of construction practices.

Table 7 Variations of Life Cycle Assessment

Acronym	Concept	Definition
LCA	Life cycle assessment	Compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle
LCI	Life cycle inventory analysis	Phase of life cycle assessment involving the compilation and quantification of inputs and outputs for a product throughout its life cycle
LCIA	Life cycle impact assessment	Phase of life cycle assessment aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts for a product system throughout the life cycle of the product
–	Life cycle interpretation	Phase of life cycle assessment in which the findings of either the inventory analysis or the impact assessment, or both, are evaluated in relation to the defined goal and scope in order to reach conclusions and recommendations
ILCD	International reference life cycle data system	ILCD consists of the ILCD Handbook and the ILCD Data Network. It provides governments and businesses with a basis for assuring quality and consistency of life cycle data, methods and assessments

Source: Cabeza et al. (2014:395)

The specialized literature on LCA tools presents several definitions depending on the objective of the analysis, the availability of information, the level of detail required to be reached with the analysis. Ramesh et al (2010) and Cabeza et al. (2014), among other authors, discuss different definitions and LCA methodologies, as described in the Table 7 above.

Table 8 LCA Studies Implemented Worldwide

Author (s)	Year	Method(s) used	Building type	Country
Adalberth	1997a; 1997b	LCA	single-unit dwellings	Sweden
Utama & Gheewala	2008	LCE		Indonesia
Utama & Gheewala	2009	LCA	high rise buildings	Indonesia
Treloar et al.	2000	LCE		Australia
Fay et al.	2000	LCE	Two-storey Detached housing	Australia

Source: Ramesh et al 2010.

The results of the bibliographic review reflect that the use of LCA methods for the assessment of energy in buildings has been carried out since the 90s, as can be seen in the *Table 8*. Likewise, the methodology has been implemented worldwide in different types of housing, ranging from single-unit dwellings to high-rise buildings. The review of these publications showed that several variations of LCA methodologies have been applied to assess building's embodied energy.

Table 9 Summary of LCA Tools and Developers

Tool	Developer	Country
ATHENA™ Experimental Impact Estimator	ATHENA Sustainable Material Institute	Canada
BEAT 2002	Danish Building Research Institute (SBI)	Denmark
BeCost (previously known as LCA-house)	VTT	Finland
BEES 4.0	U.S. National Institute of Standards and Technology (NIST)	USA
BREEAM	Building Research Establishment (BRE)	UK
EcoEffect	Royal Institute of Technology (KTH)	Sweden
EcoProfile	Norwegian Building Research Institute (NBI)	Norway
Eco-Quantum	IVAM	Netherlands
Envest 2	Building Research Establishment (BRE)	UK
Environmental Status Model (Miljöstatus)	Association of the Environmental Status of Buildings	Sweden
EQUER	École de Mines de Paris, Centre d'Énergétique et Procédés	France
ESCALE	CTSB and the University of Savoie	France
LEED	U.S. Green Building Council	USA
LEGEPs (previously known as Legoe)	University of Karlsruhe	Germany
PAPOOSE	TRIBU	France
TEAM™	Ecobilan	France

Source: Cabeza et al. 2014:399

As mentioned in the preceding sections, both the available methodologies and the databases for LCA analysis are very diverse. The *Table 9* shows the variety of available tools, databases and developers for the LCA in the different phases of the life cycle of buildings. The choice of method for choosing a method for the calculation usually depends on the purpose and scope of the task, the required level of detail, the acceptable level of uncertainty, and available resources, namely: data, time, human resources, know-how and budget (Birgisdottir et al. 2017).

Considering the reflexions mentioned above, mainly those related to the purpose of the calculations and the availability and type of data for this research, the decision was made to use a local methodology and database. In any case, the results obtained can be compared with the results of similar research in the field, as can be seen in the discussion.

III. Main Findings

As mentioned in the *Research Methods* section, a four-step (bottom-up) process analysis was conducted. In the first step, building elements were selected, followed by a mass analysis, a life cycle analysis based on ÖKOBAUDAT, and a comparative scenario analysis of the alternatives. An overview on the material composition for each scenario is to be found in the *Table 2*.

The data for the analysis was calculated based on the quantities of building materials emerging from the real case of a newly built housing complex of the company GESOBAU in Berlin, Germany. The characteristics of the housing complex are detailed in section *The Case Study*. Based on this information, a set of indicators was calculated based on the ÖKOBAU database. Thus, as mentioned in the *Selected Indicators from ÖKOBAUDAT* section, the most relevant indicators for the research are Primary Energy Non-Renewable - Total (PENRT) and Global Warming Potential (GWP). The indicator PENRT sums up the primary energy consumed from non-renewable productions, in general. On the other hand, the GWP indicator is a measure of how much heat a greenhouse gas traps in the atmosphere up to a specific time horizon, relative to carbon dioxide.

The overall research objective is to explore the contributions building's embodied energy to global CO_2 emissions by analysing a newly constructed residential building in Berlin. Therefore, the main findings will be presented by focusing on PENRT and GWP indicators, mainly.

1. Primary Energy Non-Renewable – Total (PENRT) Analysis

The calculations presented in sections below followed two approaches. First, the embodied energy of the different building components of the BAU-scenario, based on the PENRT analysis, were compared among themselves. Second, the embodied energy (PENRT values) of all three scenarios were compared as well as across the different components. The main results of each scenario and each set of indicators are detailed in the subsections below.

a) Business as Usual (BAU) Scenario

The following figure summarizes the results of the BAU-scenario which reflects the current construction standards of GESOBAU. It shows, that the major part of the embodied energy (68%) is caused by the reinforced concrete. 44% of this value is caused by concrete (C20/25 and C25/30), 56% by the reinforcement steel as these components are very energy intense. In contrast, masonry (sand-lime brick) and insulation (XPS and rock wool) only contribute for 18% or 13%. On the one hand, the materials have lower specific embodied energy demand. On the other hand, less mass was used for the construction, which in turn leads to lower embodied energy overall. Doors (1%) have nearly no effect on the total embodied energy and thus are negligible.

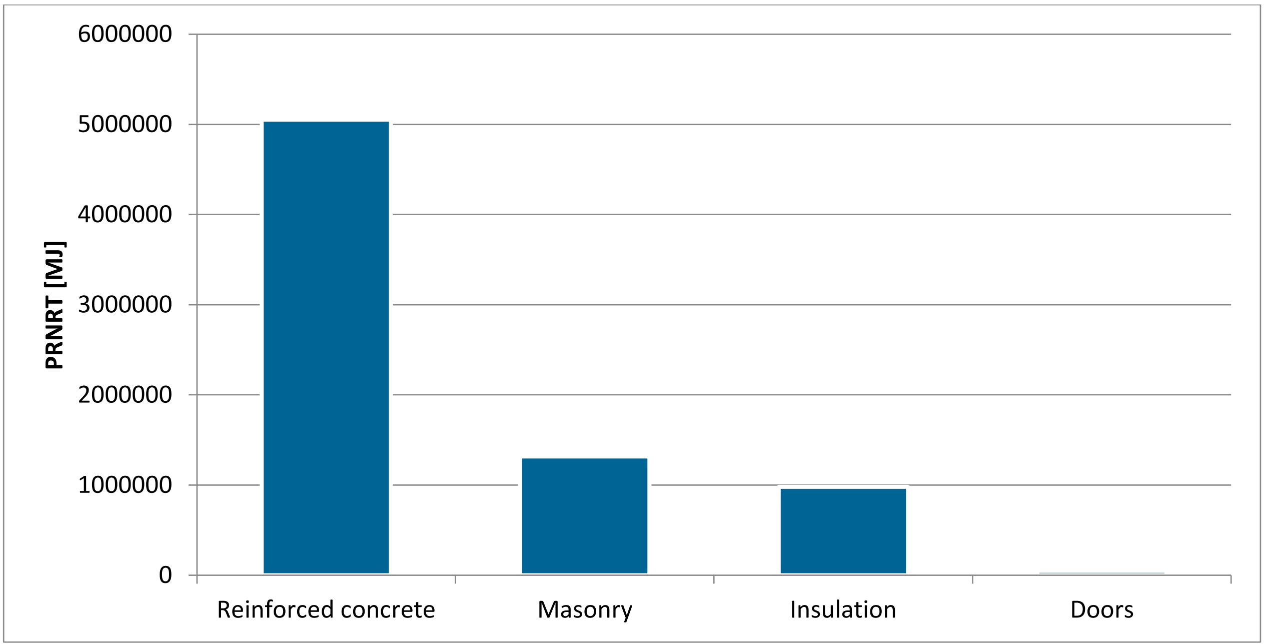

Figure 3 PENRT Analysis – BAU-Scenario

Source: Own calculations based on ÖKOBAU

b) Lower Embodied Energy (LEE) Scenario

The LEE scenario represents the same construction with changes in three materials. Rammed clay wall is used instead of sand-lime brick, cork insulation replaces rock wool insulation and doors are manufactured from wood instead of metal. Although this change of materials has no effect on the statics or functionality of the construction, the embodied energy varies significantly from the BAU scenario. The following figure shows, that especially the usage of a different material for the masonry has a huge impact on the demand for embodied energy. 93% of the embodied energy of this building component can be saved by using rammed clay wall. Furthermore, the comparison shows, that the usage of cork insulation enables a reduction of embodied energy demand to about 50% of this component. In total the proportions change as follows. 88% of the embodied energy is now caused by reinforced concrete while only 10% is caused by insulation and 2% is caused by masonry. Doors have no effect at all.

The changes within doors and masonry are solely based on lower specific values of the embodied energy, as the measured masses do not change. In contrast, the lower values of insulation are caused by lower specific values as well as changes in masses used. The masses were calculated based on a target U-value.

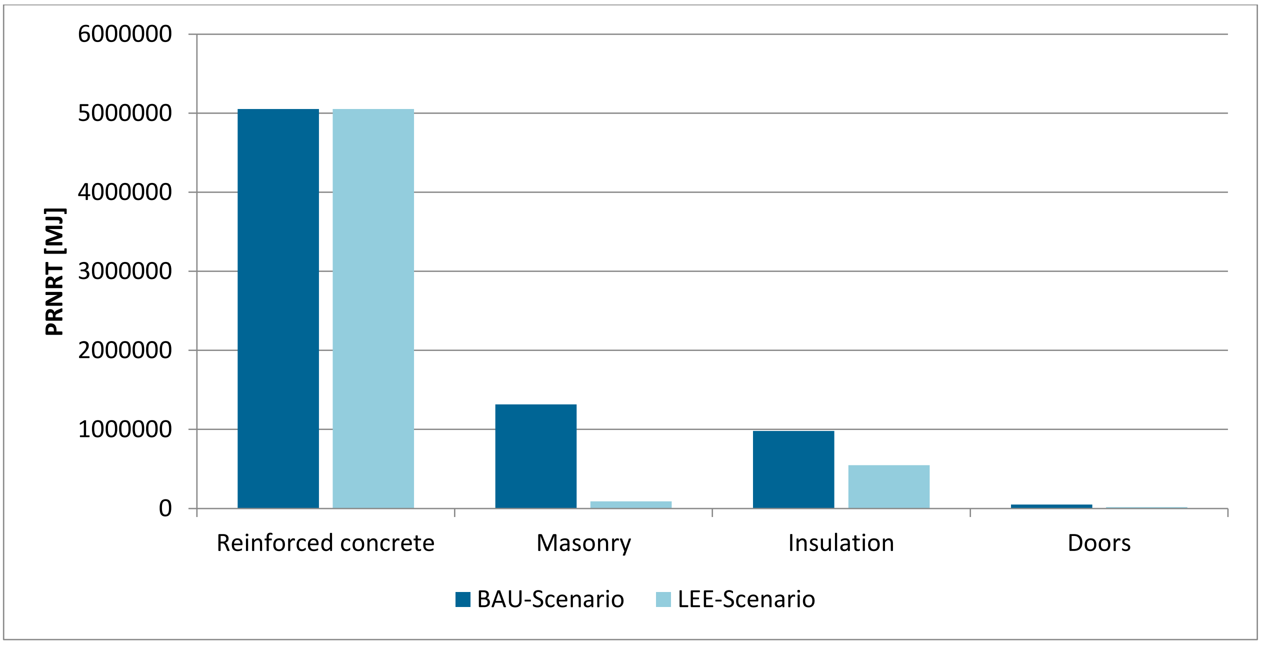

Figure 4 PENRT Analysis – LEE-Scenario

Source: Own calculations based on ÖKOBAU

c) Higher Embodied Energy (HEE) Scenario

The HEE scenario represents the same construction with changes in one material, as compared to the BAU-scenario. Only one material was changed, since the materials used for masonry and doors already have a comparably high specific embodied energy. This scenario shows, that especially the usage of a different material for the insulation can also have a significant negative impact on the demand for embodied energy. The usage of wood fiber insulation instead of rock wool results in about 50% more embodied energy demand for this building component.

In total the proportions change as follows. Only 61% of the embodied energy is now caused by reinforced concrete while 16% is caused by masonry and 22% is caused by insulation. Doors are still negligible. The lower values of insulation are caused by lower specific values as well as changes in masses used. The masses were calculated based on a target U-value.

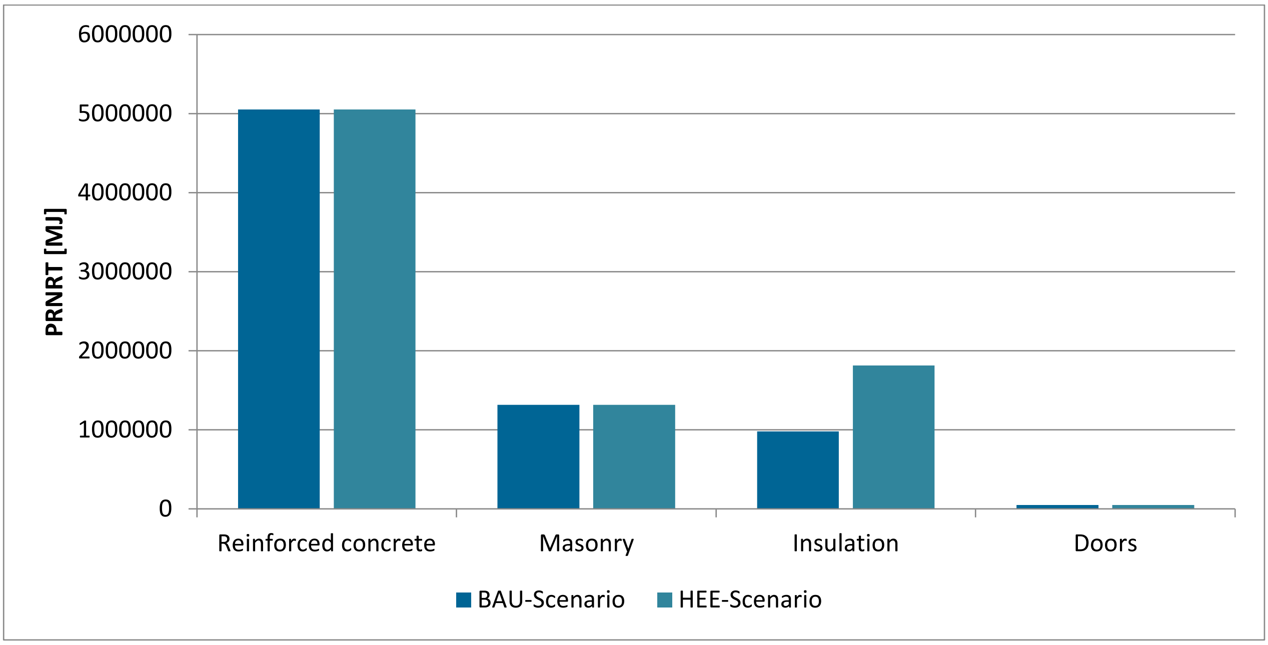

Figure 5 PENRT Analysis – HEE-Scenario

Source: Own calculations based on ÖKOBAU

d) Comparative Analysis

The following *Figure 6* represents all changes in the material composition that enabled the calculations for each scenario, as explained in the above sections. The usage of different materials for masonry, insulation and doors leads to significant changes in demand for embodied energy. Especially different insulations come with high potentials.

Moreover, the embodied energy of each building element can be compared between the different scenarios. This PENRT values are relevant since every building component has a significant and different contribution to every scenario. The comparative analysis shows, that the LEE scenario reduced the embodied energy by nearly 20% when compared to the BAU scenario. In contrast, different materials can also cause 8% higher embodied energy in the HEE scenario, as shown in the *Figure 6* below.

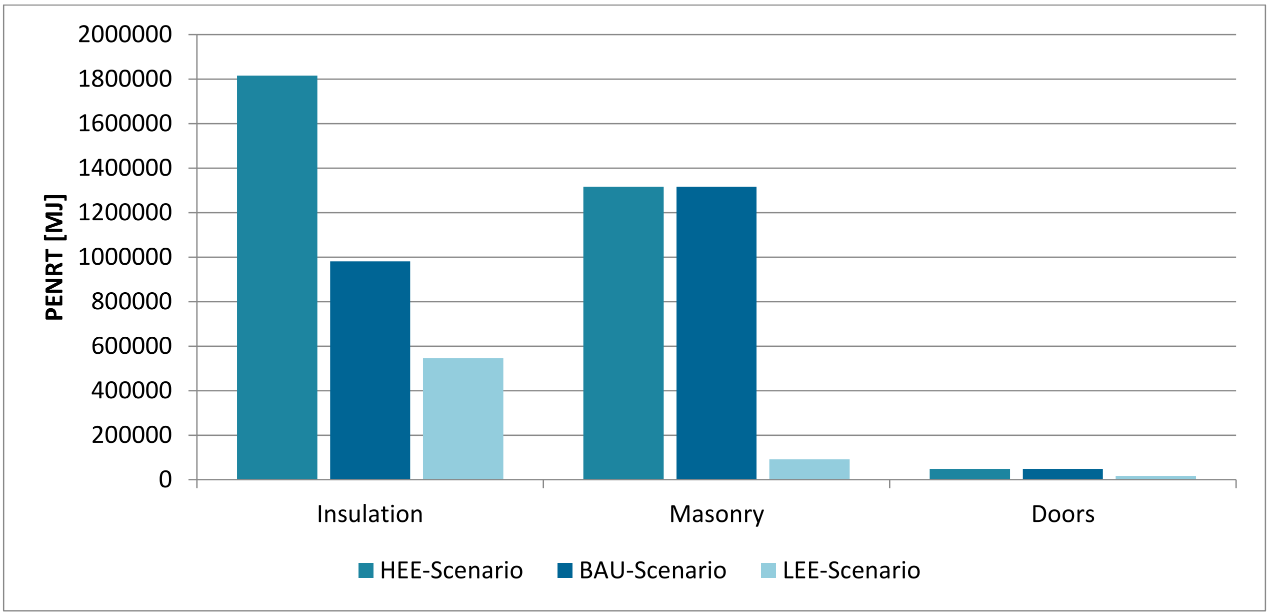

Figure 6 PENRT Comparative Analysis – all Scenarios & Building Components

Source: Own calculations based on ÖKOBAU

A comparative analysis of the three scenarios clearly shows the comparative advantages of implementing materials with lower embodied energy that allow a decrease of almost 20% compared to the BAU-Scenario. On the other hand, although the HEE-Scenario shows higher values than the BAU-Scenario because high values available on the ÖKOBAU platform were selected, it is likely that these materials form part of buildings currently constructed in Berlin. The empirical evidence gathered in this research, however, does not support this hypothesis.

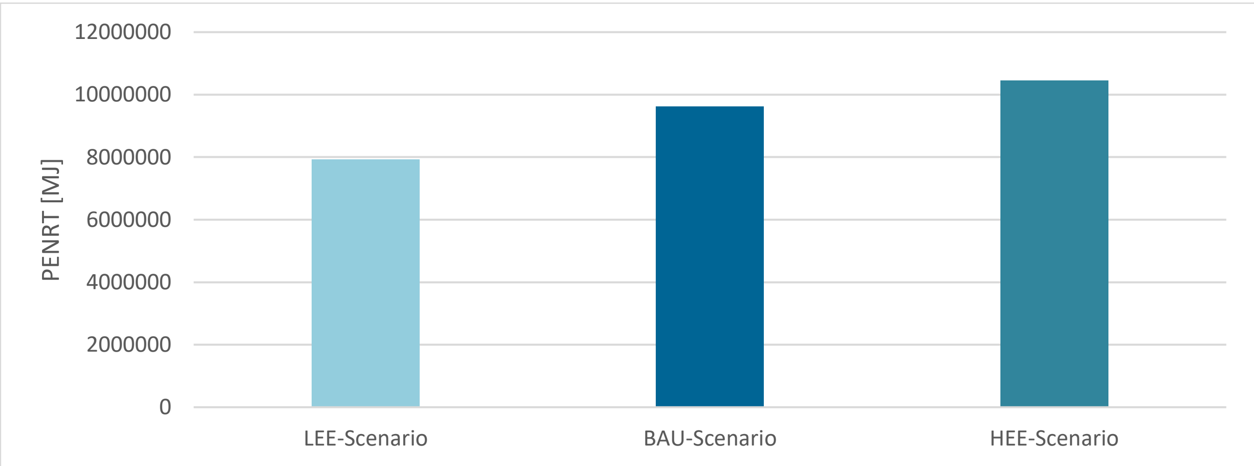

Figure 7 PENRT Comparative Analysis - All Scenarios

Source: Own calculations based on ÖKOBAU

2. Global Warming Potential (GWP) Analysis

The calculations presented in sections below followed two approaches. First, the measures of how much heat a greenhouse gas traps in the atmosphere up to a specific time horizon, relative to carbon dioxide of each building component, based on the GWP analysis, were compared among themselves.

Second, the GWP values of all three scenarios (namely BAU-, LEE-, and HEE-Scenarios) were compared as well as across the different components. The main results of each scenario and each set of indicators are detailed in the subsections below.

a) Business as Usual (BAU) Scenario

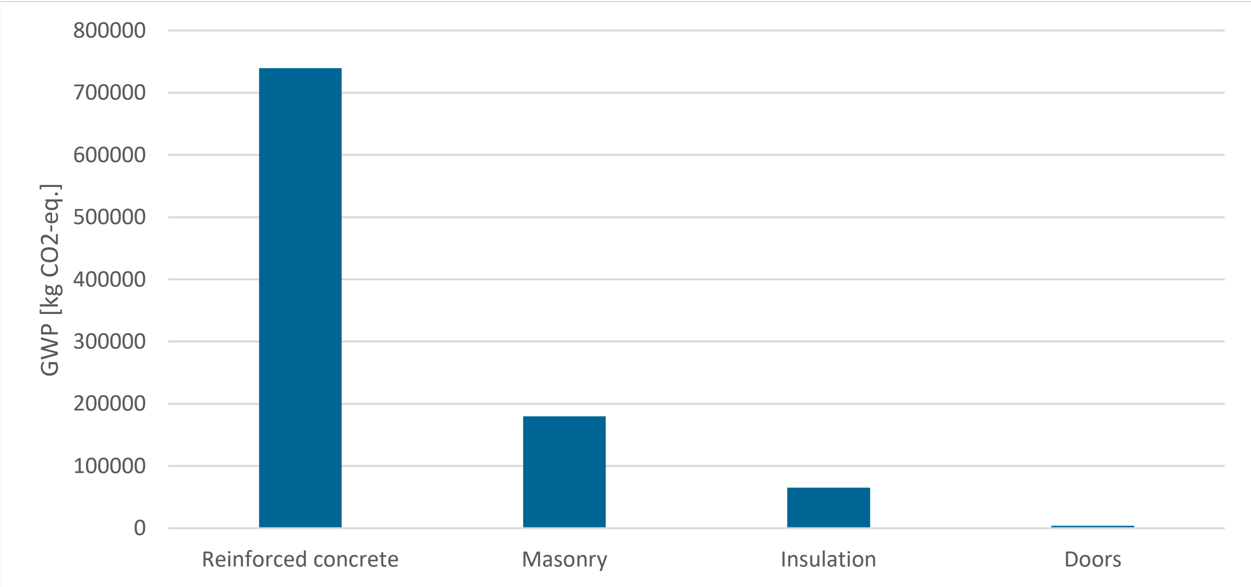

Figure 8 GWP Analysis – BAU-Scenario

Source: Own calculations based on ÖKOBAU

The analysis of GWP of the individual components in the BAU scenario showed significant differences for the selected building elements. As it can be seen in the *Figure 8*, reinforcing steel causes by far the most CO2 emissions (over 700000 kg CO2-eq). The distribution of the values for the other building elements is quite similar to the results found with the PENRT analysis. Masonry and insulation also cause CO2 emissions, but significantly only a fraction of the emissions of the reinforcement steel. Doors CO2 emissions can be neglected.

b) Low Embodied Energy (LEE) Scenario

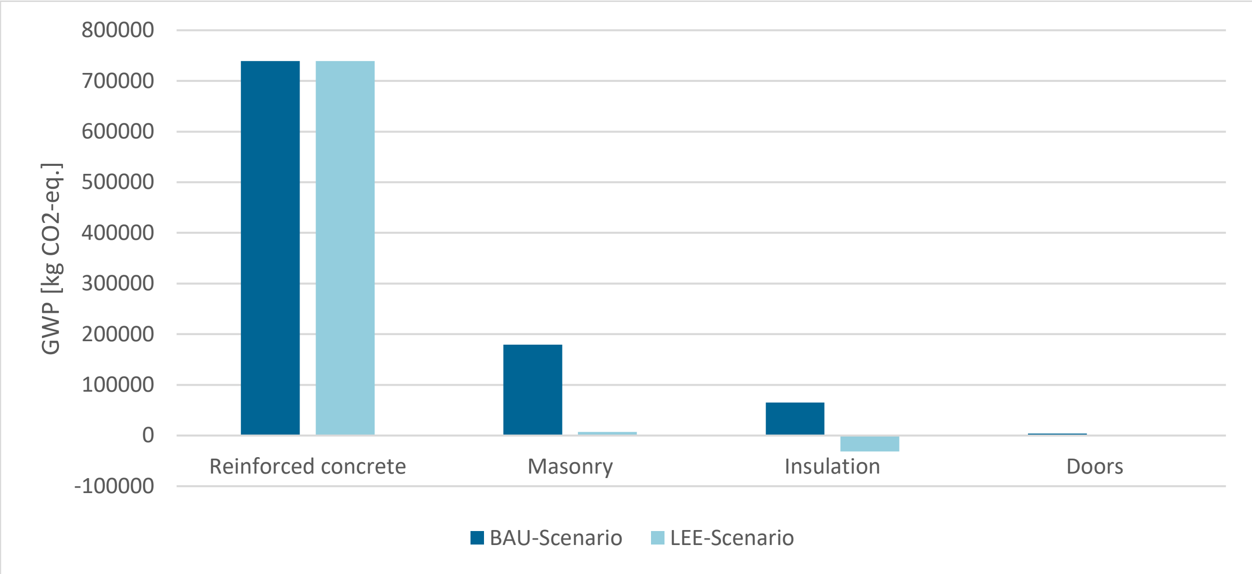

Figure 9 GWP Analysis – LEE-Scenario

Source: Own calculations based on ÖKOBAU

When comparing the LEE-scenario with the BAU-Scenario, it becomes evident that when selecting alternative building materials with lower embodied energy, considerable CO2 savings can be achieved with Masonry and insulation, as shown in the *Figure 9*. In the case of insulation, the use of cork as insulation material, it can even save CO2. This is expressed by a negative GWP value. This means that the raw material used in the insulation stores more CO2 than is emitted for the manufacture of the component. This consideration is the decisive difference to the consideration of materials embodied energy. This considers only the energy used and is therefore never negative. However, it is important to consider that the CO2 is released again in later phases during the end of life if the material is disposed and not recycled. By burning or rotting the wood, the CO2 returns to the air or soil. When considering only A1-A3, however, the use of wood often leads to negative values, as the raw material usually stores more CO2 than is emitted during the manufacture of the component.

c) High Embodied Energy (HEE) Scenario

The GWP analysis of the HEE-Scenario shows the same phenomenon observed in the LEE-Scenario. Although the embodied energy is higher than in the BAU scenario, the GWP values are lower or equal, as shown in the *Figure 10*. The use of a wood fiber, as material insulation, leads to the storage of CO2 during the building construction and operation phases. Therefore, the GWP values are negative, although the production of the insulation material shows higher embodied energy values, compared to alternative isolation materials, like rock wool and cork insulation as considered in the alternative scenarios. This means that the same conditions are not observed as with embodied energy.

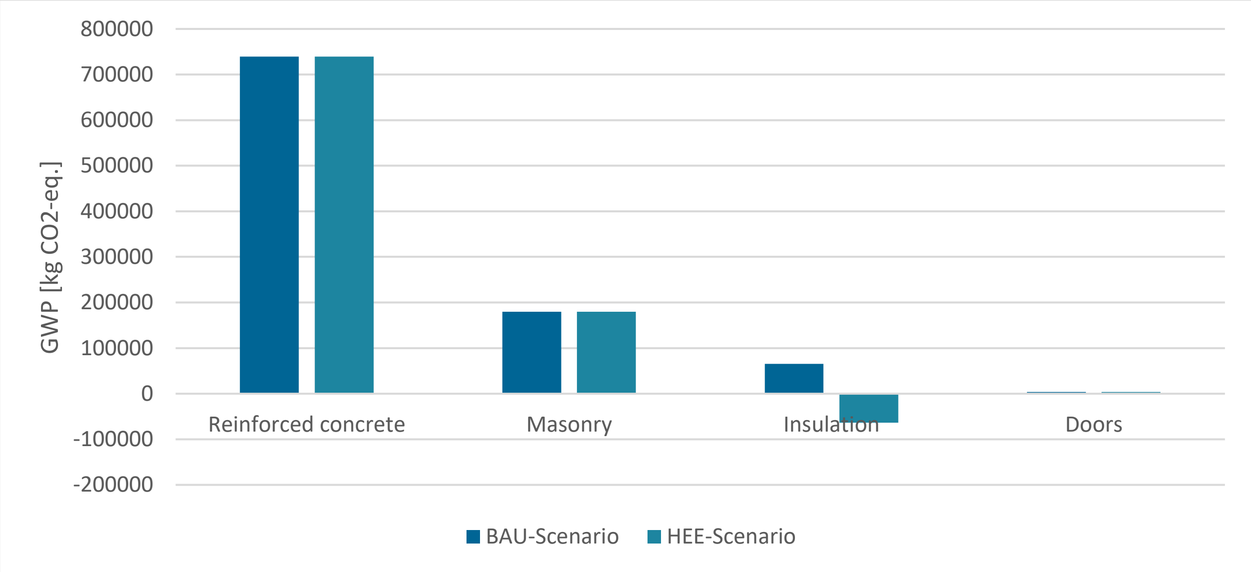

Figure 10 GWP Analysis – HEE-Scenario

Source: Own calculations based on ÖKOBAU

d) Comparative Analysis

Overall, it can be said that both changed scenarios have ultimately shown a lower GWP value than the BAU scenario. Nonetheless, the HEE scenario has a higher embodied energy value, as shown in *Figure 11* below. This can be attributed to the fact that wood, selected as alternative material for different building components in the different scenarios, stores CO2 during certain phases of its lifecycle.

Therefore, the differences between the individual scenarios are evident but not enormous. This is because reinforced concrete is used in all scenarios for static elements. However, this could also be replaced by a wooden construction. (This wasn't done here because the masses would look completely different and I couldn't see how much wood would be needed instead of reinforced concrete. This did not allow me to do any calculations. One could point out, however, that one should carry out such a comparison in the future, since wood stores CO2 and thus usually shows a negative GWP. See wood fibre insulation above). This could even lead to negative GWP values. This means that the production of the considered components of the building even absorbs CO2 instead of emitting it. This is due to the CO2 storage capacity of the raw material wood.

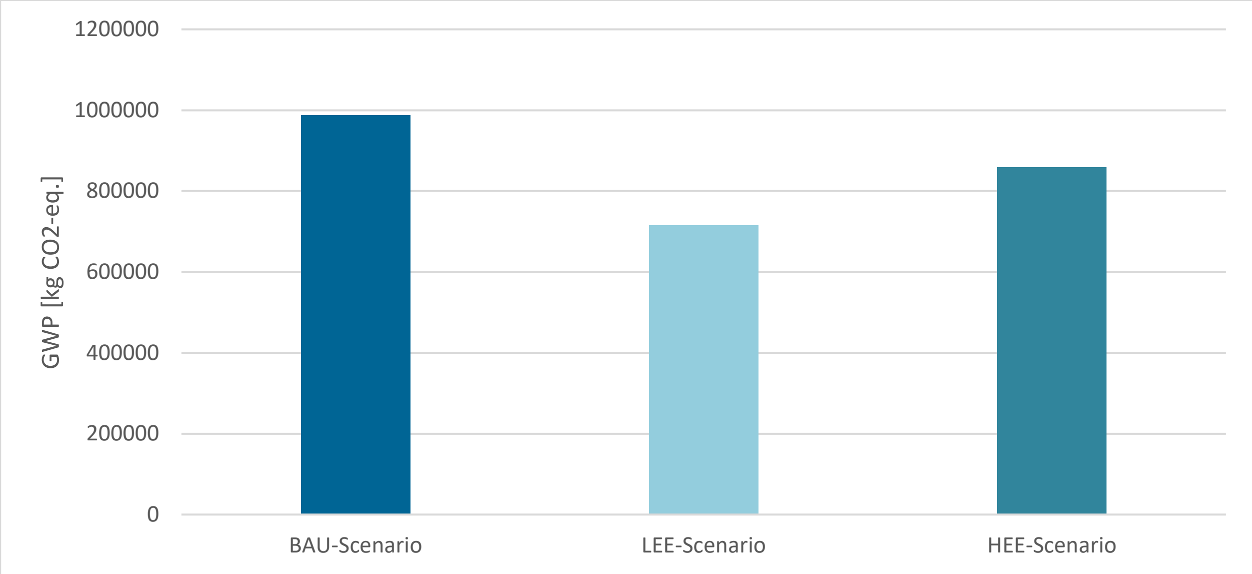

Figure 11 GWP Comparative Analysis – all Scenarios & Building Components

Source: Own calculations based on ÖKOBAU

IV. Discussion

According to the Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety (BMBU 2016) the building stock in Germany should be climate-neutral by the year 2050. This is a very ambitious goal which, in the case of the building sector, cannot be achieved if all phases of the life cycle of buildings are not considered. To this end, nevertheless, the government's Climate-Friendly Building and Housing Strategy considers the findings of the Strategy on Energy Efficiency in Buildings and the Alliance for Affordable Housing and Building (see DENA 2016). The Strategy on Energy Efficiency in Buildings, which has already been adopted, illustrates how the goal of achieving a virtually climate-neutral building stock by 2050 can be achieved through a combination of energy efficiency and renewable energy (BMBU 2016). Moreover, the framework for climate-neutral buildings and locations developed by the German Sustainable Building Council (DGNB) makes the global climate protection targets manageable for the various decision-makers in the construction and real estate industries by providing a reliable orientation on how CO2 emissions can be reduced continuously and to the necessary extent. It should help to make the decarbonisation of existing buildings feasible by 2050 and help to make climate neutrality the standard for new buildings.

It is difficult to foresee, however, if these policy goals will be enough to achieve the decarbonization goals set for the sector. According to the Federal Chamber of Architects (Bundes Architekten Kammer or BAK) the transformation to a climate-neutral building stock requires a fundamental change of direction. BAK (2018) states the focus must not be on saving energy, but on climate protection, and suggest that in addition to energy savings in the heating sector, the focus should include sustainable material cycles and economical use of material and surface resources. What is needed is a holistic view of the building and a holistic strategy for reducing buildings CO_2. From this perspective, 'holistic' means an extension of the system boundary in three respects, namely: 1) from the use phase to the life cycle, by considering energy and CO_2 balance of buildings over the entire life cycle; 2) from the individual building to the neighbourhood, since the current focus of the energy saving law on individual buildings does not go far enough; and 3) from the individual view of the building sector to the cross-sector view, since an efficient transformation of the energy system will only succeed through a coordinated interaction of the different sectors (BAK 2018:42).

Construction is one of the most resource-intensive sectors of the economy. In Germany alone, 517 million tons of mineral raw materials are used annually. This corresponds to 90 percent of the total domestic extraction (Zentrum Ressorcenefizienz 2019). The annual use of structural steel (5.5 million tonnes[3]) and cement (26.6 million tonnes[4]) is also considerable, which in total means that the German building stock now comprises an estimated 15 billion tonnes of material (anthropogenic material storage for building construction).[5] Moreover, over 209 million tonnes of construction and demolition waste flow from the construction sector each year, which corresponds to 52 percent of the German waste volume.[6] At the same time, this use of raw materials offers great savings potential, which is why the construction industry plays a key role in implementing resource efficiency.

The results of this research contribute significantly to achieving the national targets set for the sector as they seek to address the decarbonization of the sector from the design stage of buildings by considering materials with lower embodied energy. This means considering a holistic perspective that considers the entire life cycle of the building (design, construction, operation, and demolition) to go beyond the reduction of CO2 emissions implemented energy efficiency measures only in the operating phase of the building.

Empirical evidence shows that a large percentage of the amount of materials used for the construction of the residential building in the case study is reinforced concrete. As mentioned in the analysis, this component presents significantly higher embodied energy values with respect to other building elements/materials. From a broader perspective, it is necessary to highlight that this traditional form of construction of high-raise residential buildings, as reflected in GESOBAU's case study, has significant repercussions globally in terms of CO2 emissions generated by using cement as an essential material of reinforced concrete. According to a recent publication by FAZ (2019) the cement industry is one of the largest emitters of climate-damaging greenhouse gases, but it is still a silent one because is hidden in building's structure and streets all over the world. The World Wildlife Fund (WWF in FAZ 2019) has estimated its share of global emissions at 8 percent, which would be significantly more than the total volume of air traffic.

[3] See BMU (2012:73)
[4] See VDZ (2016:4)
[5] See Mülle et al. (2017)
[6] See Destatis (2017:58)

V. Conclusions

The primary objective of the research is to explore the contributions building's embodied energy to global CO_2 emissions. The research findings indicate that there is a significant potential for the reduction of embodied energy in newly constructed residential buildings in Berlin.

The literature review conducted within the research served to collect and analyse relevant information for the construction of the theoretical framework and the methodological framework of the research. The theoretical discussion provided insights about the energy considerations in residential buildings in two main phases within their life cycle, i.e. embodied energy and operational energy; the implications of CO2 emissions in both phases were also discussed. The methodological framework reviewed tools and methods for building's embodied energy calculations found in the relevant literature. Moreover, the literature review showed, that one of the main constrains for implementing such analysis is data availability. This issue was partially addressed thanks to the active collaboration between science and practitioners enabled trough the Kopernikus Enavi project between IKEM and GESOBAU. The later enabled the primary data availability for analysis in the context of this research, namely the case study provided by GESOBAU, it was decided to use the database of the ÖKOBAUDAT for the building lifecycle analysis, so the results obtained could be brought closer to the reality of the materials existing on the German market.

The results of the LCA analysis show that the use of materials with lower embodied energy in residential buildings in Berlin can result in a significant reduction of about 20% when comparing the PENRT values between the LEE-Scenario scenario and the BAU-Scenario scenario. In the case of the GWP values the alternative materials showed significant differences in the values for wood-derived building elements. This is because wood (or its derivatives) captures CO2 in the manufacturing and operating phases of the product, however, the reduced emissions return to the atmosphere or subsoil at the end of life stage of the building materials or elements. The latter leads to two meaningful considerations: 1) the importance of adequate recycling that allows the CO2 capture achieved by the materials to continue to be part of the life cycle of the building; and 2) the need for an exhaustive analysis of the life cycle of buildings and products made from wood, which allows discussing sustainability in their use and the real contributions to global CO2 capture.

Further research

This research provides relevant information for the discussion of the contribution of embodied energy from residential buildings to global CO2 emissions. Moreover, the research contributes to the discussion about methodologies and tools available in Germany.

On the basis of the information obtained within the research, the following lines of research are opened:

In cooperation with GESOBAU.

- The analysis of the research focused on a single company residential building. It would be relevant for future research to analyse other case studies of the same company in order to know the CO2 footprint of its buildings.
- On the other hand, the construction of scenarios for the comparison of the LCA analysis were taken arbitrarily, through the selection of materials with lower and higher embodied energy from ÖKOBAUDAT. It would be interesting to discuss their plausibility with private sector experts by means of a qualitative inquiry.
- The research was solely focused on building's embodied energy and did not address any issue related to building's operating energy, mainly because the case study selected for analysis is a new building that was not yet occupied; therefore, data on energy consumption in the operating phase were not available. Nonetheless, it would be interesting to explore with qualitative tools the energy use of the building during the operation phase in order to explore saving potentials within the entire life cycle of the building

Analysis of the sector's embodied energy

- On the basis of the research results the question arises as to which will be the behaviour of the embodied energy of the rest of the buildings of the residential stock in Berlin. The scientific literature accounts for the relevance of the building typology in the analysis of the CO2 contributions of the sector. Therefore, it is relevant to analyse the embodied energy of other building types, in order to find potentials for CO2 capture for each type of residential buildings. Likewise, the analysis of commercial and public buildings could contribute significantly to a holistic analysis of the sector.

- An investigation of this nature, however, requires a different methodological approach to that used in this study. On the one hand, the volume of data is significantly greater, just as the sources of information are very diverse. However, a study of this magnitude can make a significant contribution to reducing emissions from the sector and thus to achieving the long-term goals set by the German Government.

- Taking into consideration the goals set out in the relevant German legislation, it is recommended to consider a holistic assessment for buildings and their building materials over their entire life cycle, which considers the embodied energy, for elaborating climate protection goals within for the built environment sector. For this purpose, manageable and practice-oriented methods and tools for sustainability assessment in a future energy saving law could be considered. Starting points for the classification are to be found in the ÖKOBAUDAT, in which evaluation points for the use of resources are stored. Moreover, keeping in mind a transition towards achieving climate goals that go beyond energy efficiency standards, a climate certificate – which considers both embodied and operating energy in the overall evaluation of the building – could replace the current energy certificate in the future,

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