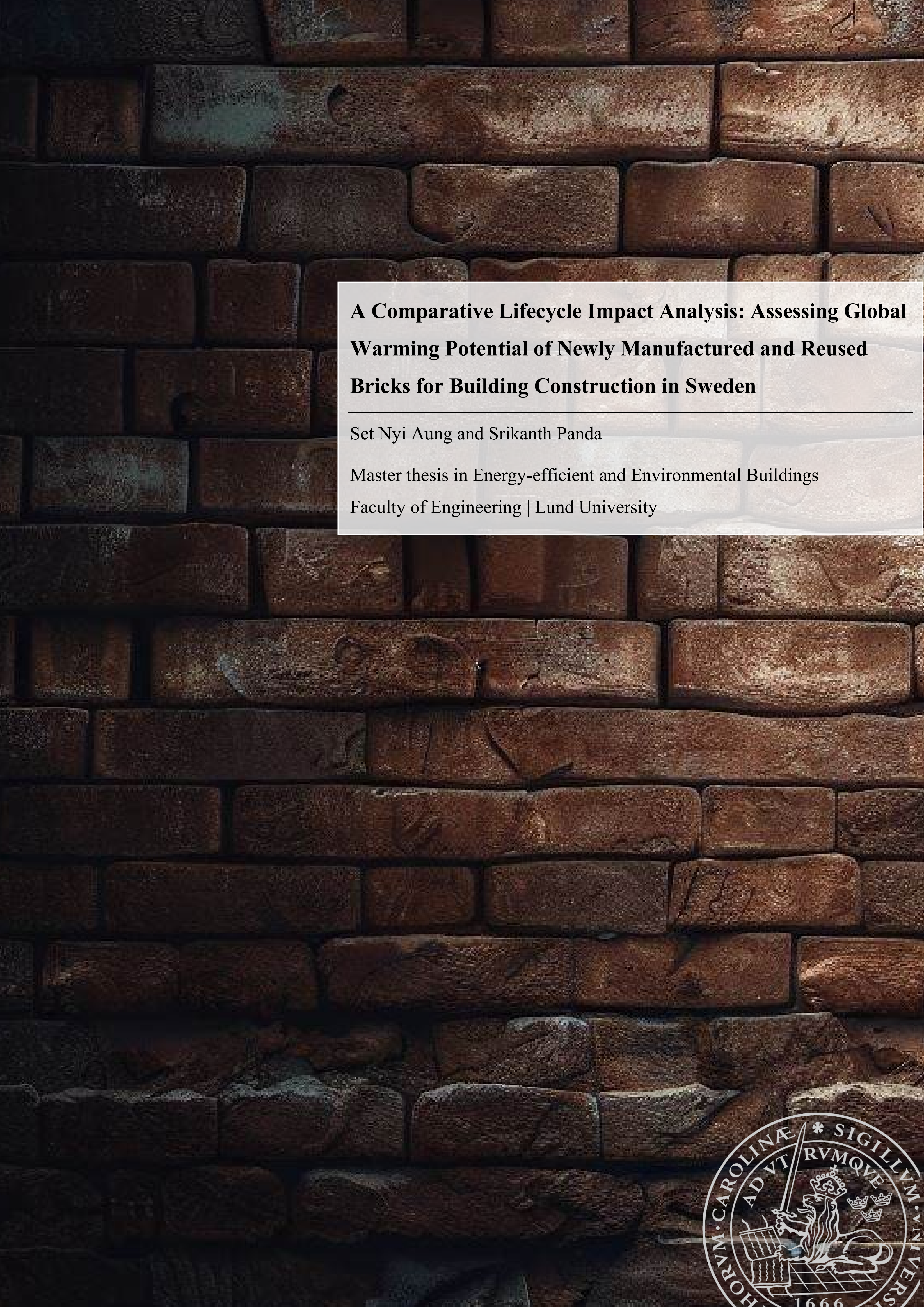

A Comparative Lifecycle Impact Analysis: Assessing Global Warming Potential of Newly Manufactured and Reused Bricks for Building Construction in Sweden

Set Nyi Aung and Srikanth Panda

Master thesis in Energy-efficient and Environmental Buildings
Faculty of Engineering | Lund University

Lund University

Lund University, with eight faculties and a number of research centres and specialized institutes, is the largest establishment for research and higher education in Scandinavia. The main part of the University is situated in the small city of Lund which has about 112 000 inhabitants. A number of departments for research and education are, however, located in Malmö. Lund University was founded in 1666 and has today a total staff of 6 000 employees and 47 000 students attending 280 degree programmes and 2 300 subject courses offered by 63 departments.

Master Programme in Energy-efficient and Environmental Building Design

This international programme provides knowledge, skills, and competencies within the area of energy-efficient and environmental building design in cold climates. The goal is to train highly skilled professionals, who will significantly contribute to and influence the design, building or renovation of energy-efficient buildings, taking into consideration the architecture and environment, the inhabitants' behaviour and needs, their health and comfort as well as the overall economy.

The degree project is the final part of the master programme leading to a Master of Science (120 credits) in Energy-efficient and Environmental Buildings.

Examiner: Dennis Johansson (Division of Building Services)

Supervisor: Ulla Janson (Division of Building Services), Karin Farsäter (Division of Building Services), Carl Hansson (Brukspecialisten AB)

Keywords: Newly manufactured Bricks, Reused Bricks, Lifecycle Impact Assessment, GaBi ts, openLCA

Publication year: 2023

Table of content

List of Abbreviations

ASBP	Alliance for Sustainable Building Products
CE	Circular Economy
C2C	Cradle to Cradle
CO_2	Carbon Dioxide
CPCR	Country-specific Product Category Rules
DU	Declared Unit
ELCD	European Reference Life Cycle Data System
EoL	End-of-life stage
EoW	End-of-waste stage
EPD	Environmental Product Declaration
EU	European Union
FU	Functional Unit
GHG	Greenhouse Gas
GWP	Global Warming Potential
GWP100a	Global Warming Potential 100 years
IPCC	Intergovernmental Panel on Climate Change
$kgCO_2eq$	Kilogram Carbon Dioxide Equivalent
kWh	Kilowatt hour
LCA	Lifecycle Analysis
LCI	Lifecycle Inventory
LCIA	Lifecycle Impact Assessment
PCR	Product Category Rules
PO	Program Operator
RSP	Reference Study Period
SEK	Swedish Krona
TBE	Tiles and Brick Europe

List of figures

List of tables

Abstract

The study aims to compare the environmental performance in terms of Global Warming Potential (GWP), for reused bricks and newly manufactured bricks used in Swedish Construction Industry. The objective of the study was to compile and conduct Life Cycle Assessment (LCA), in terms of GWP, of newly manufactured and reused clay façade bricks used in Sweden. Cradle-to-cradle lifecycle impact of new and reused clay façade bricks was calculated by utilising product-specific data and Swedish national scenarios. GWP impact was accessed for the primary energy source used in the product stage and its overall impact throughout the product lifecycle. The product type and the end-of-life scenario with the least GWP impact were identified through data analysis.

The GWP data of 128 clay façade bricks were obtained from the published type III Environmental Product Declarations (EPD) by European Program Operators. Product-specific data and Boverket Klimatdatabas scenarios were used to recalculate the impacts in LCA software to suit the Swedish national scenarios. The parametric study was conducted in LCA software, GaBi ts and openLCA, to evaluate the impact on the product's lifecycle due to the application of various energy sources in the product stage. The obtained data were compiled in Excel and analysed using Tableau and Python to identify the case with the lowest GWP.

It was found that reused bricks had the lowest lifecycle impact in terms of GWP compared to newly manufactured bricks concurrently being financially beneficial. The study concludes the whole lifecycle impact of a product not only depends on the product stage resource consumption, but also on the reuse, and recycling potential. The best method to lower the GWP of new bricks was to manufacture using cleaner, renewable fuels with greater reuse potential.

Acknowledgement

As the authors of the study, we would like to express our sincere gratitude to our supervisor Ulla Janson and co-supervisor Karin Farsäter for the guidance and support extended throughout this project. Their knowledge and expertise were invaluable for the successful completion of this project. We are grateful for the time they invested in the study. We would also like to thank Carl Hansson of Brukspecialisten for providing valuable insight into reused brick manufacturing and the input values for the study.

Personal acknowledgements from Set Nyi Aung

I would like to express my heartfelt gratitude to my friends and family for their unwavering support throughout my academic journey. I would also like to extend my sincere appreciation to the Swedish Institute for awarding me the SISGP scholarship for my studies. This scholarship has not only provided me with much-needed financial assistance but has also allowed me to pursue my academic goals. Last but not least, I want to acknowledge my partner, Srikanth Panda, for his invaluable support and dedication.

Personal acknowledgements from Srikanth Panda

I would like to express my heartfelt appreciation to my family and friends for their constant support and encouragement throughout the duration of the programme. I would also like to acknowledge the generosity of Lund University for awarding me the Lund University Global Scholarship which has not only relieved my financial burden but also boosted my morale. Lastly, I would like to extend my gratitude to my project partner, Set Nyi Aung, for his unwavering support and dedication towards the successful completion of this report. His contributions have been invaluable and have greatly enhanced the quality of the work.

Contributions

The literature review and collection of Environmental Impact data from Environmental Product Declarations were conducted simultaneously by both authors. Subsequently, the collected data were subjected to analysis and visualisation using Tableau and Python by Set Nyi Aung, while Srikanth Panda carried out the Life Cycle Impact Assessment calculations in GaBi ts and openLCA. Lastly, the report was written collaboratively by both authors.

Preface

This study is a compulsory part of academic requirements in the curriculum for conferment of a Master's degree in Energy-efficient and Environmental Building Design at Lund University, offered at campus Helsingborg in Sweden. This study is a result of the collective effort by the authors under academic supervision and using the data provided by Brukspecialisten. Environmental Product Declarations of new and reused bricks published in Europe formed the basis for the study, later Lifecycle Impact Assessment was performed in LCA software and results were presented.

(This page is intentionally left blank)

1. Introduction

1.1 Background

The construction industry, a critical sector of the global economy, is responsible for more than 40 % of the world's Greenhouse Gas (GHG) emissions (Lechner, 2015). Bricks are an indispensable part of building construction and are used in almost every project in varying quantities. This project focuses on clay façade bricks, intending to provide insight into the environmental benefits of reusing building materials by carrying out a detailed Lifecycle Impact Assessment comparison of newly manufactured bricks and reused bricks with a cradle-to-cradle approach. This project seeks to aid informed decision-making for the construction industry by providing a comprehensive analysis of the 100-year Global Warming Potential (GWP100a) associated with circular materials by studying brick as a case example. In this report, the acronym GWP is used interchangeably for GWP100a value, and all the GWP values hereon mentioned are GWP100a values.

1.2 Literature review

1.2.1 Circular economy and its challenges

The concept of Circular Economy (CE) was coined by British environmental economists, David W. Pearce and R. Kerry Turner in the year 1990 in their book titled *Economics of Natural Resources and the Environment.* According to Pearce and Turner (1990), to address the issues of resource scarcity and waste disposal, all open-loop processes should be converted into closed-loop systems (David W & R. Kerry, 1990). Circular Economy can be explained as 'where the value of products, materials and resources is maintained in the economy for as long as possible, and the generation of waste minimised' (EEA, 2015). Reusing and recycling used products at the End-of-life stage form the bases of the closed-loop system reducing waste and the need for virgin materials (Yu et al., 2014).

However, to adopt CE as an economic model for the future, immense reforms at the societal and policy level will be needed. Some of the barriers to implementation can be technological, policy and regulatory, financial, and economic, managerial, performance indicators and socio-cultural (Araujo Galvão et al., 2018). Due to a lack of awareness of the benefits of circular materials, implementation of CE policies by businesses and the government can be challenging (Rizos et al., 2016). It could be intriguing to find viable strategies and initiatives capable of driving economic growth while alleviating environmental pressure (Zhang et al., 2009).

A study conducted by Ottosen et al. (2021) on the implementation of CE policies in the Danish building construction sector identified a need for methods for documenting the economic and environmental gains, technical methods for documenting the quality of reused materials, processes which enables scaling and development of new value chains for reused materials (Ottosen et al., 2021). The resource-intense construction industry contributes to approximately 50% of all extracted resources and over 35% of the total waste generated within the European Union (EU). The processes of material extraction, manufacturing of construction products, and construction and renovation of buildings contribute to about 11 % of the total national GHG emissions in the EU (UNEP, 2021).

Traditionally, construction and demolition waste was landfilled, which contaminated groundwater and surrounding habitats. Materials such as clay brick, aluminium, concrete, and ceramics have a high environmental impact due to their mass and associated energy-intensive manufacturing processes. Recycling demolition waste at the end-of-life stage instead of landfilling can lower the overall environmental impacts by 22 %. Reusing and recycling building materials in the construction stage can reduce total impacts by 43 %. Ceramic construction materials like roof tiles and façade bricks with longer reference service life of more than 150 years can lower the embodied energy of buildings. Construction materials like bricks with a higher recycling potential of over 80 % can reduce the overall environmental impact if recycled or reused at the end-of-life of buildings (Papadaki et al., 2022).

1.2.2 Measuring the environmental impact of products

The environmental impacts of construction products or whole buildings can be measured by conduction a Lifecycle Impact Assessment (LCIA). An Environmental Product Declaration (EPD) of a product is a standardised document that provides information about the environmental impact of products for a part or their entire lifecycle. EPDs are usually developed following international standards such as ISO 14025 and EN 15804 enabling transparency and comparability for informed decision-making through harmonisation. Harmonisation initiatives are becoming widely recognised to increase the significance and comparability of EPDs on a global scale (Minkov et al., 2015).

However, according to Gelowitz & McArthur (2017), a valid comparison between the EPDs of the materials can be made only if they fulfil the listed criteria:

a) The EPDs in comparison have either the same functional or declared unit or can be converted into a common unit.
b) The LCA system boundaries are the same or common lifecycle sub-module that can be compared.
c) The same characterisation factors are used, or they can be easily convertible with conversion factors mentioned for specific categories.
d) Contains all mandatory content as per ISO 14025, namely, the description of the product, Product Category Rules (PCR) identification, publication date, validity period, secondary data information, the listing of materials and substances to be declared, and information on the excluded stages in the LCA.
e) Identical Cut-off rules are used for the percentages of mass, energy, and environmental impact permitted to be excluded from the calculation.

As per the need of the industry for harmonisation, standards such as EN 15804 were created acting as a "Core PCR" to aid in improved compatibility within categories. EPDs made using the PCRs written to this standard can be reliably compared (Gelowitz & McArthur, 2017). The additional information on cut-off rules and allocation procedures as well as the PCR or sub-PCR used while making the EPDs will further enhance their comparability (Moré et al., 2022).

1.2.3 Challenges in performing LCA of reused construction materials

The availability of reliable input data to perform LCIA of reused products is essential (Kinuthia et al., 2018). According to EN 15804, the primary data used for LCIA should be less than 5 years old and the secondary data should be less than 10 years old (SIS, 2021). Additionally, the primary data used should be obtained from average values of more than 12 months of recorded data. The secondary data used for LCIA can be obtained from LCA Databases like MLCA Database (formerly known as GaBi Database) and Ecoinvent and also from national databases like Boverket's Klimatdatabas. Despite the constant improvements, there are still errors in these databases due to incorrect flows, and wrong or absent characterisation factors that can lead to inaccurate conclusions (Pauer et al., 2020).

1.2.4 Clay bricks and their environmental impact

Bricks, with their energy-intensive manufacturing processes and significant mass, make a substantial contribution to the overall environmental impact of buildings (Papadaki et al., 2022). However, their longer RSL and excellent recyclability have the potential to significantly mitigate the lifecycle impact of buildings. Oti & Kinuthia (2012) highlights that the emissions associated with clay brick production are primarily attributable to the high energy use of brick manufacturing kilns during the calcination process which requires an internal temperature greater than 1 050 °C for extended periods (Oti & Kinuthia, 2012).

Conversely, the findings of (Bovea et al., 2007) indicate that in the context of red clay utilised in the ceramic industry, the most notable contribution to the environmental impact originates from excavations, loading, and transportation to the crushing factories and stock points. However, the exclusion of impacts arising from excavations, loading, and transportation to the manufacturing units can be achieved through adherence to product-specific PCRs such as TBE (Tiles & Brick Europe, 2014). This discrepancy raises questions regarding the reliability of emissions reported in EPDs. Consequently, it becomes imperative to undertake a re-evaluation of the environmental impact of these products, employing consistent input data and PCR Methodology. Boverket Klimatdatabas asserts that the energy use associated with manufacturing one kilogram of bricks varies between 2.0 to 4.0 MJ of non-renewable energy and 0.5 MJ of electricity, values that have been adopted for this study (Boverket, 2022).

1.2.5 Missing knowledge

While some studies have focused on modelling the lifecycle of reused products, there is currently a lack of PCR specifically addressing circular materials. The determination of the percentage of demolition materials that can be effectively converted into reuse bricks or recycled brick aggregates is subjective, and no national scenarios for Sweden were referenced in the PCR. Consequently, values received from the company Brukspecialisten were used in this study and adapted for the lifecycle Module D impact assessment.

Following the recommendations of Ekvall et al. (2020), this study assumed that the product stage impacts of reused bricks would be equivalent to the impacts associated with demolition, transportation, cleaning, and packaging of the bricks (Ekvall et al., 2020). However, the study did not account for the impact of land transformation or the greenhouse gas emissions resulting from the burning of clay during the manufacturing of new bricks. These aspects present opportunities for further investigation.

1.2.6 Outline of the methodology and structure of the report

To conduct the study, clay bricks EPDs published by European Program Operators were collected. The Environment Impact data, especially, GWP values were compiled along with other information like, primary energy type used, PCR followed, functional unit specified, allocation type selected, and national scenarios adopted for the end-of-life stage. As the EPDs for reused bricks were limited, product stage impacts were calculated using the annual average data of the year 2022 provided by Brukspecialisten. The median value of all EPDs for new bricks was assumed for the product stage due to a lack of manufacturing-related information.

As the assumptions used in these EPDs were not the same and judged unsuitable for bricks used in Sweden, Boverket Klimatdatabas recommended values were assumed as Swedish national scenarios. Whole life cycle GWP impact was recalculated using LCA software, GaBi ts and openLCA, for both new and used bricks using different End-of-life (EoL) scenarios and primary fuel types, using the values provided by Brukspecialisten and those obtained from literature using the same PCR Methodology. Thus, obtained data were analysed using Tableau and Python and the results are presented. This report is structured into four main chapters. The detailed methodology is described in Chapter 2 of this report. The results of the data analysis and LCIA interpretation are presented in Chapter 3 followed by the discussion and conclusion in chapters 4 and 5, respectively.

1.3 Aim and Objectives

The study aims to compare the environmental performance in terms of GWP, for reused bricks and newly manufactured bricks used in Swedish Construction Industry. The functional unit used is one tonne of bricks.

To fulfil the aim of the project, the following objectives were considered:

- To compile and evaluate the lifecycle impact, in terms of GWP, of newly manufactured and reused clay façade bricks used in Sweden.
- To calculate the cradle-to-cradle (C2C) lifecycle impact of new and reused clay façade bricks by utilising product-specific data and Swedish national scenarios.
- To determine the global warming potential impact of the primary energy source used in the product stage and its overall impact throughout the product lifecycle.
- To compare and identify the product and the end-of-life scenario with the least GWP impact.

The detailed methodology adopted for achieving these objectives is presented in Chapter 2.

2. Method

The methodology outlines the comparative LCA of new and reused brick products. The study comprises three main sections: EPDs analysis, LCA modelling of reused brick, and LCIA using openLCA and GaBi ts.

2.1 Analysis and Evaluation of EPDs

Section 2.1 details the methodology employed for the analysis of EPDs. This section is subdivided into three parts: sample selection, data collection of EPDs, and analysis of EPDs.

2.1.1 Sample Selection

2.1.1.1 Type of Brick

The type of bricks considered in the study was mainly clay bricks which were either moulded or extruded and fired in high-temperature kilns used as façade bricks. Clay bricks are known for their durability, strength, and aesthetic appeal, but their production can have significant environmental impacts, especially in terms of energy use and GHG emissions. Therefore, investigating the environmental performance of clay bricks through EPDs can provide valuable insights for the construction industry, policymakers, and consumers seeking to make more sustainable choices.

2.1.1.2 Geographic Region

To ensure regional representativeness of the brick manufacturing process, the primary geographic location for this study was focused on Europe. This decision was driven by the extensive production of clay bricks in Europe and the availability of EPDs adhering to the EN15804 standard. Furthermore, as indicated by Boverket, Sweden does not contain brick manufacturing facilities, thus relying on imports from neighbouring countries including Denmark, Finland, the Netherlands, Belgium, and Germany (Boverket, 2022). By analysing EPDs of clay bricks manufactured in these countries, the present study aims to provide valuable insights into the environmental performance of clay bricks utilised in Sweden. However, it is essential to acknowledge that variations in production methods, raw materials, national scenarios employed, LCA database, and methodology employed to generate the EPDs may render the findings unsuitable for direct comparison.

2.1.1.3 Scope and Data Quality

The EPDs analysed in this study used a C2C lifecycle approach, ranging from Module A to Module D, and utilised diverse functional units. The research focused solely on the GWP impact category, as the principal aim was to investigate the climate change impact of the products. To ensure a valid comparison, only EPDs with compatible PCR adhering to the EN15804 standard were included, despite variations in product-specific PCR and different versions of the EN15804 standard across the selected EPDs (SIS, 2021).

2.1.1.4 Availability & Credibility

The methodology for obtaining EPDs of clay bricks in Europe was informed by the "ASBP Briefing Paper - EPD: Where to find them?" by the Alliance for Sustainable Building Products (ASBP) and Jane Anderson. This paper guided where to find EPDs, how to assess their quality and reliability, and how to interpret the data presented in them (Jane Anderson, 2020).

The ASBP paper recommended several sources for finding EPDs of building products, including manufacturers' websites, trade associations, and EPD databases such as the International EPD System as shown in Table 2-1. The paper by Gelowitz (2017) also advised that EPDs should be selected based on their adherence to recognized standards, such as ISO 14025 and EN 15804, and their compatibility with the PCR of the specific product being evaluated (Gelowitz & McArthur, 2017).

Table 2-1 EPD Databases

Continent	Country	Database Name
Europe	All	European Platform on LCA Eco Platform International EPD System
	Austria	Bau-EPD: Building Materials, Product Declarations, Product Rating
	Denmark	EPD Denmark
	Finland	RTS EPD | Rakennustietosäätiö
	France	INES | Les données environnementales et sanitaires de référence pour le bâtiment PEP Ecopassport
	Germany	Institut Bauen und Umwelt e. V. ÖKOBAUDAT - Standardized Database
	Ireland	Irish Green Building Council - EPD
	Italy	EPD Italy
	Netherlands	Dutch – National Milieudatabase MRPI.nl
	Norway	EPD Norge - EPD-Norge Digi/ILCD+EPD EPD Norway
	Poland	Strona Glówna - Poland EPD
	Portugal	DAPHabitat - Published EPD
	Slovenia	ZAG - Zavod za gradbenistvo - Issued EPD
	Spain	AENOR - GlobalEPD declarations in effect DAPconstrucción - Catalonia
	Sweden	EPD Library | EPD International
	Switzerland	SUGB - EPD
	Turkey	EPD Turkey
	United Kingdom	ASBP Member EPD Database GreenBook Live IMPACT | BRE Group

By following the guidance provided in the ASBP Briefing Paper, this study identified and collected EPDs of clay bricks adhering to the EN 15804 standard. The credibility of the EPD provider and their reputation within the brick industry were also assessed to ensure the accuracy and reliability of the data presented in the EPD. This methodology provided a comprehensive and rigorous approach to obtaining and evaluating EPDs of clay bricks in Europe.

However, obtaining EPDs was challenging due to various factors. One challenge was that not all EU countries used the same platform, such as ‘Eco Portal’, to host EPDs. As a result, EPDs had to be searched individually in each database, which was time-consuming. Furthermore, the formatting of EPDs differed for each country, making it hard to automate the process of retrieving information from them. As a result, each EPD had to be read and evaluated manually, which was resource intensive. Another challenge was that some EPDs were written in different languages, which was a barrier to accessing the information they contained. To obtain the necessary information from these EPDs, Google Translate or other translation tools was used, which could have introduced errors or inaccuracies to the translation. Therefore, while EPDs provided valuable information on the environmental impact of products, obtaining them was a complex and challenging process that required significant time and resources.

2.1.2 Data Collection of EPDs

Based on the criteria mentioned by Gelowitz & McArthur (2017), suitable EPDs for analysis and evaluation were selected. The criteria ensured that the EPDs were comparable and provided accurate data on the environmental performance of new and circular bricks. The selection process considered factors such as availability, validity, completeness of data, and relevance to the study. The selected EPDs were used to compare the environmental performance of new and reused bricks and to evaluate the accuracy of existing EPDs for bricks (Gelowitz & McArthur, 2017).

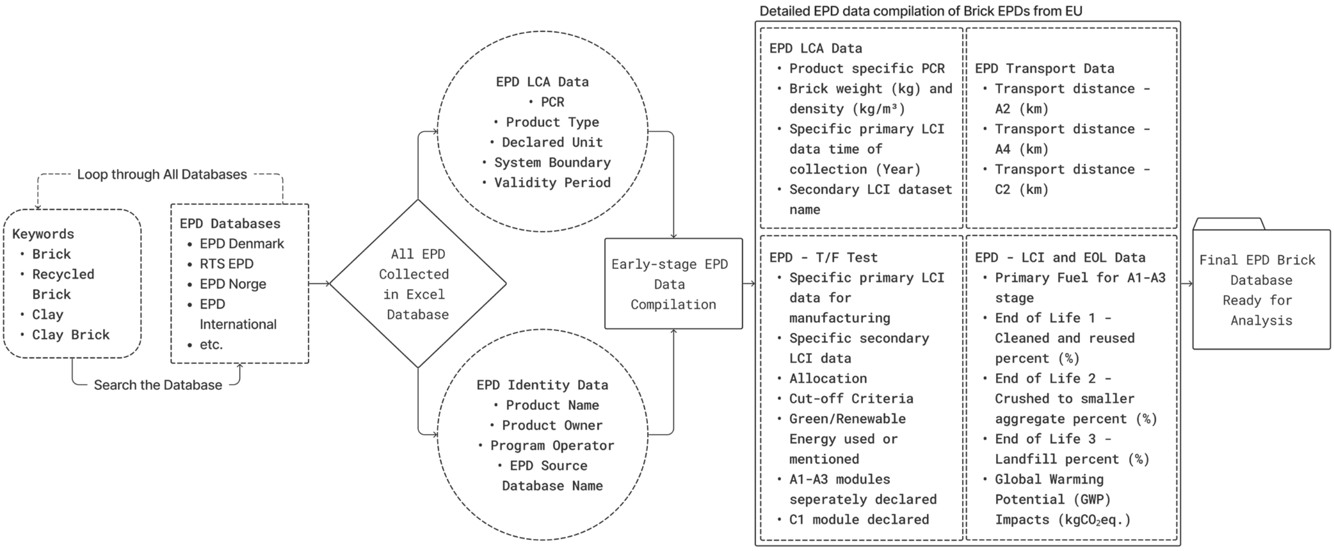

Figure 2-1 EPD Collection Workflow

To obtain and evaluate EPDs of clay bricks, a comprehensive methodology was developed as shown in Figure 2-1. The methodology consisted of five steps listed below:

- Step 1: Searching for Type III EPDs of clay bricks in various EPD databases using keywords such as "brick," "recycled brick," and "clay".
- Step 2: Create an Excel database with early-stage EPD data, such as product name, product owner, program operator, EPD source database name, PCR, product type, declared unit, system boundary, and validity period (Microsoft, 2022).
- Step 3: Analysing and sorting all the collected EPDs according to their quality and relevance.
- Step 4: Filtering out the EPDs that are not from the EU or that do not meet the minimum requirements for comparability and validity.

- Step 5: Collect detailed EPD data from each remaining EPD and add them to the database. The data include product-specific PCR, brick weight and density and created a conversion factor to 1 tonne, specific primary Lifecycle Inventory (LCI) data for manufacturing, specific primary LCI data time of collection, specific secondary LCI data, secondary LCI dataset name, allocation, cut-off criteria, transport distance for A2, A4, and C2 stages, the primary fuel for A1-A3 stages, green/renewable energy used or mentioned, separately declared A1-A3 modules, C1 module declared, EoL 1 - cleaned and reused per cent, EoL 2 - crushed to smaller aggregate per cent, EoL 3 - landfill per cent, and GWP100a impacts.

This methodology overcame some of the challenges encountered in obtaining and evaluating EPDs of clay bricks in Europe, such as variations in formatting and language barriers. It provided a rigorous and systematic approach to assessing the environmental performance of clay bricks in Europe. The final EPD brick database with the EPD case number can be found in Appendix A. This compiled GWP100a data and other product information from the EPDs will be referred to as the "EPD database" in this study.

2.1.3 Analysis of EPDs

Using the final brick EPD database created from the previous steps, the data was imported to Tableau 2023.1 for comprehensive analysis (Tableau, 2023). The first set of analyses investigated was to assess the accuracy and comparability of the EPDs. The following aspects were investigated:

- Distribution of product types: The aim was to determine the number of brick EPDs and reused brick EPDs that have been published.
- PCR and Product Specific or Core PCR: This analysis aimed to identify the dominant PCR currently being used in the industry and determine the comparability.
- Declared unit of EPD: The purpose was to ascertain the majority of declared units used in brick EPDs and to determine the most appropriate declared unit for bricks.
- Specific primary LCI data time of collection: This analysis aimed to determine the age of primary LCI data obtained from factories and suppliers, to assess their reliability.
- Secondary LCI datasets used: The goal was to identify the commonly used LCI datasets for secondary data, such as transportation and energy flows.
- A1-A3 modules declared separately: This analysis aimed to determine the transparency of EPDs concerning the mining of clay and energy use for production.
- C1 module declared: This analysis aimed to investigate the inclusion of demolition stage impacts.
- A4 and C2 modules transport distance: The aim was to identify the most common distance for transportation in the A4 and C2 modules.
- Allocation and Cut-off criteria: To determine the accuracy of the EPDs and conduct further investigation into the reasons for allocation.
- The primary fuel for the A1-A3 stages: This analysis aimed to determine the most used fuel types for brick production, to further analyse their impacts.

- Green/Renewable energy used or mentioned in production: The purpose was to assess the proportion of brick production that utilised green and renewable energy, and to evaluate its accuracy through LCIA calculations.
- EoL scenarios percentage: This analysis aimed to identify the EoL scenarios declared in the EPDs, and to determine whether clean and reused bricks were considered in the EPDs.

Following the initial analysis, the GWP of bricks was further investigated using median and percentile calculations. Firstly, the GWP of all EPDs in the brick database was analysed, which provided an overall picture of the environmental performance of bricks, regardless of the production location or primary energy source used. By calculating the median and percentile values, it was possible to identify any extreme outliers and investigate any variations in the GWP among different bricks. For the second analysis, the GWP of bricks was examined based on the country of production. This analysis aimed to identify any significant differences in the environmental performance of bricks across different geographic regions. As for the third analysis, the GWP of bricks was evaluated based on the primary energy source used for production. This analysis aimed to identify any differences in environmental performance for bricks produced using different energy sources, such as hard coal, natural gas, or renewable energy.

2.2 Lifecycle Impact Assessment (LCIA) using openLCA and GaBi ts

The present study undertakes a comparative analysis of the environmental impacts associated with the use of newly manufactured and reused bricks in Sweden, where brick manufacturing facilities are non-existent, as mentioned earlier. The environmental data for both types of bricks were obtained through EPDs, but due to differences in national scenarios, databases, and PCR methodology, it was not possible to compare them directly. Thus, a decision was made to model the lifecycle of both products within the same LCA software, employing a consistent database and PCR methodology. The study utilised EN15804-A2 2019 as the core PCR and TBE 2014 PCR as the product-specific PCR for the analysis (SIS, 2021; Tiles & Brick Europe, 2014).

The production-specific data for reused bricks were collected from Brukspecialisten, based on the annual average values for the year 2022. However, the production-specific data for new bricks, required to estimate their associated emissions, was deemed confidential and, therefore, inaccessible. Consequently, the median value of all EPDs analysed for the production stage lifecycle sub-modules was used, while country-specific scenarios were employed for the remaining modules in line with the PCRs. Energy inputs of the EoL stage of both products were obtained from data provided by Brukspecialisten.

For the comparative analysis, the functional unit assumed was 1 tonne of newly manufactured façade brick and 1 tonne of reused brick used for façade construction, respectively. The RSL of 150 years and calculation period of 50 years was adopted. A C2C approach was employed for the LCIA.

The LCIA was conducted using OpenLCA and GaBi ts software packages, each utilising a specific database and LCIA method (GreenDelta, 2022). In OpenLCA, the ELCD_3_2_greendelta_v2_18 database was employed, along with the openLCA_lcia_v2_0_5_20200610 method, to establish product systems for all processes with the appropriate inputs (JRC, 2015). The default providers were chosen to "auto-link the processes”, and the quick results were obtained by utilising the allocation method “as defined in the process”, and the IPCC 2013 GWP 100a impact assessment method. The resulting data was exported to MS Excel for further analysis.

For the GaBi ts analysis, the GaBi education version with the 2020 education database was used (Thinkstep, 2020). New plans were created to model life cycle scenarios consistent with the input and output quantities of the processes employed in the OpenLCA analysis. The appropriate flows were connected to each process in the plan, and the results were obtained using the IPCC AR5 method with the IPCC AR5 GTP100, excl. biogenic carbon [Excl. biogenic carbon] quantity and weighting, with user-defined grouping for all processes based on their contribution to the respective lifecycle sub-module. The results were also exported to MS Excel for further analysis.

2.2.1 Modelling LCIA of new brick

To perform an LCIA of newly manufactured brick, the production stage values were derived from the median values of all the relevant EPDs, as explained in 2.2. Since all newly manufactured brick in Sweden is imported and the PCR did not include country-specific scenarios for Sweden, a transportation distance of 640 km from the factory gate to the construction site was adopted as recommended by Boverket (Boverket, 2022). This transportation was assumed to be carried out by a Euro 4, 40-tonne articulated lorry powered by diesel, and the location was set to Europe. During the installation process stage (A5), it was assumed that 1000 kg of brick would require 335 kg of cement mortar to construct the facade. As a result, at the EoL stage, a dismantled brick façade would comprise 1000 kg of bricks and 335 kg of cement mortar, resulting in a total weight of 1335 kg of construction rubble requiring transportation per one-tonne brick. To model the EoL stage, national scenarios were adopted as per the PCR. Following use, the dismantled 1335 kg brick facade would generate 335 kg of waste due to the cement mortar, while the remaining 1000 kg of bricks would undergo further processing. From the processed brick content, 30% or 300 kg would be landfilled, while the remaining 70% or 700 kg would be transformed into reused bricks. Transportation distances of 39 km and 23 km were assumed from the demolition site to the recycling facility and from the recycling facility to the landfill site, respectively, following the PCR.

It was assumed that the construction stage yielded a packaging waste amount of 7.02 kg, composed of 0.46 kg of plastic waste and 6.56 kg of wooden pallet waste, in line with values derived from Brukspecialisten for 1-tonne brick packaging data. Waste processing impact was calculated based on 98.3 MJ of electrical energy generated from wind power and 0.42 litres of diesel consumption. Furthermore, the emissions resulting from waste disposal and landfilling were evaluated using 634 kg of construction waste, containing glass or inert waste, along with 0.46 kg of plastic waste. All values used for each sub-module are presented in Figure 2-2.

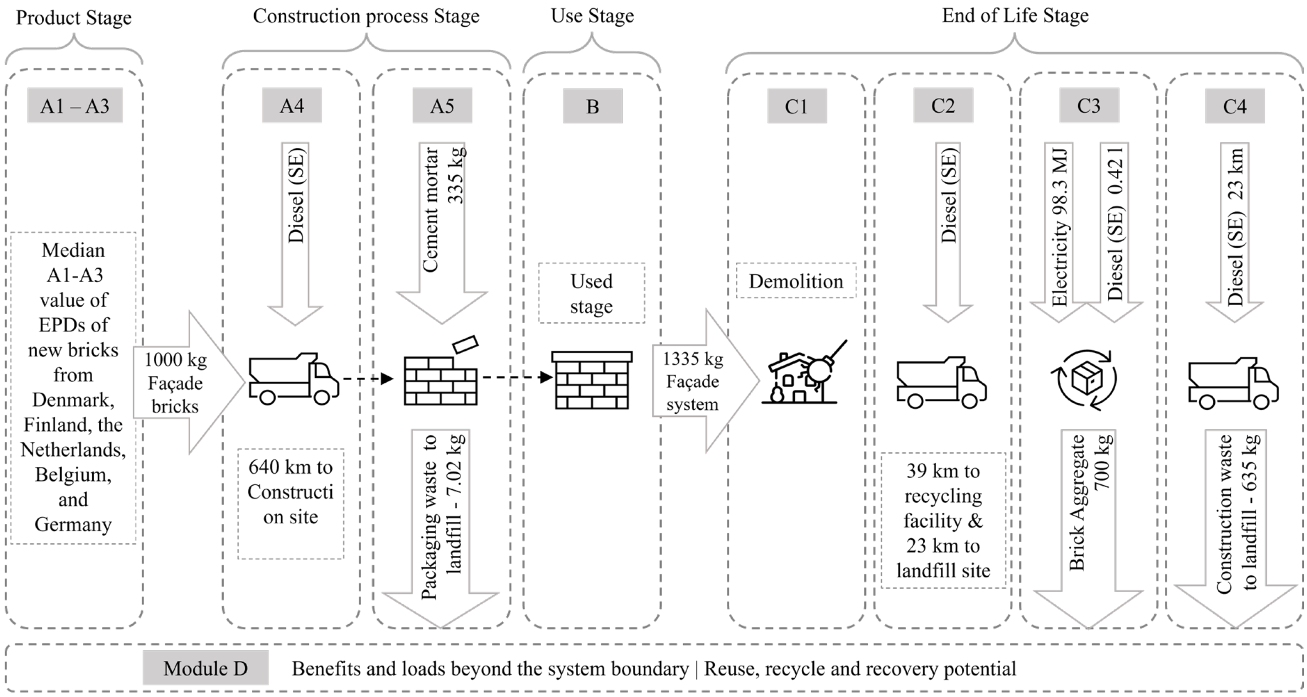

Figure 2-2 Life cycle stages and system boundaries with Inputs and outputs for newly manufactured brick

To conduct LCIA using the GaBi ts software, the input flows and processes were maintained consistent with those employed in the openLCA software for the entire life cycle. To evaluate the impact of transportation, it was assumed that a facade consisting of 1000 kg of bricks and 335 kg of cement at the EoL stage was transported over a distance of 39 km to a recycling facility. A Euro 4, 34–40-tonne truck trailer, which had a maximum payload capacity of 27 tonnes and utilised Swedish diesel mix as fuel was used as the transport. In terms of waste processing, it was assumed that 0.42 litres of diesel and 98.3 MJ of electricity from wind power were required as per the values provided by Brukspecialisten. The plastic waste, weighing 0.46 kg, and construction waste, weighing 634 kg, were transported to a landfill facility located 23 km away for disposal. The modelling plan and inputs used in the GaBi software can be found in Appendix B.

2.2.2 Modelling LCIA of reused brick

For conducting LCIA of reused brick, production stage values were adopted from the values provided by Brukspecialisten. Consistent with the recommendations of the PCR, the effects associated with the dismantlement of a wall were deemed insignificant in comparison to that resulting from the demolition of an entire building. Consequently, the raw material extraction involved in the utilisation of bricks was also deemed to have a negligible impact.

The national scenarios for recycling materials at the EoL stage provided by the PCR were utilised to determine the quantity of raw material (i.e., dismantled brick facade) required to produce 1000 kg of reused bricks. The ratio of reclaimed to landfilled material was determined to be 70:30, respectively. It was calculated that demolition waste comprised 1430 kg of bricks and 475 kg of cement mortar, with the mortar accounting for one-third of the brick's weight, resulting in a total weight of 1905 kg needed to achieve a finished product of 1000 kg of reused brick.

A transportation distance of 150 km was assumed from the demolition site to the factory gate (A2) and from the factory gate to the construction site (A4) using a Euro 4, 40-tonne articulated lorry fuelled by diesel, and the geographical location was assumed to be Europe. The sorting and cleaning of 1905 kg of construction rubble to produce 1000 kg of reused bricks consumed 140 MJ of electrical energy from wind power and 0.5 L of diesel, which were provided by Brukspecialisten. The processed bricks were packaged using 0.46 kg of plastic film and wooden pallets weighing 6.56 kg, which were subsequently sent to recycling facilities from the installation process stage (A5). In the A5 stage, it was assumed that 1000 kg of used façade brick would also need 335 kg of cement mortar for façade construction. Thus, at the EoL stage, the dismantled brick façade contained 1000 kg of bricks and 335 kg of cement mortar making the total weight transported to the recycling facility per 1-tonne brick as 1335 kg of construction rubble. The flows at various life cycle sub-modules are summarised in Figure 2-3.

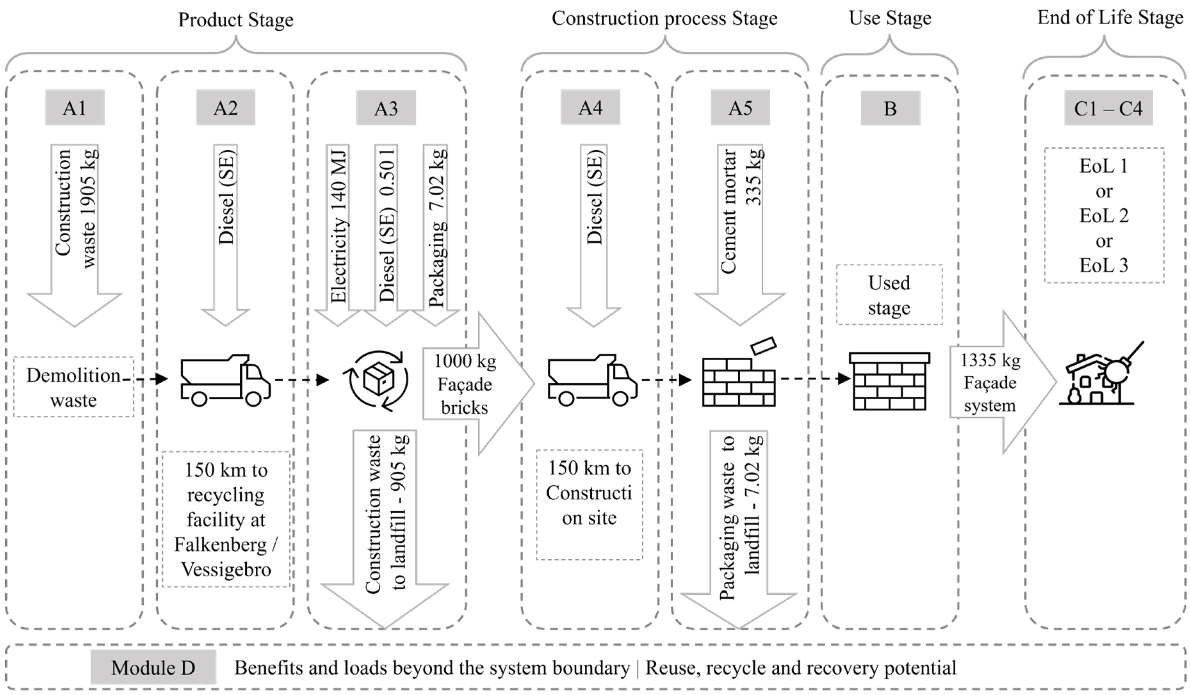

Figure 2-3 Life cycle stages and system boundaries with Inputs and outputs for reused brick

To explore the most environmentally beneficial end product during the end-of-waste stage, three EoL scenarios, outlined in Figure 2-4, were examined. As per the PCR, the energy required for dismantling the brick facades was assumed to be negligible for all three scenarios. The input for waste processing was also constant as the same quantity of waste was handled. The demolition waste was transported back to the Brukspecialisten recycling unit at a distance of 150 km via a Euro 4, 40-tonne articulated lorry using diesel fuel. Brukspecialisten provided data that showed that 0.42 L of diesel and 98.3 MJ of electrical energy from wind power were needed for waste processing.

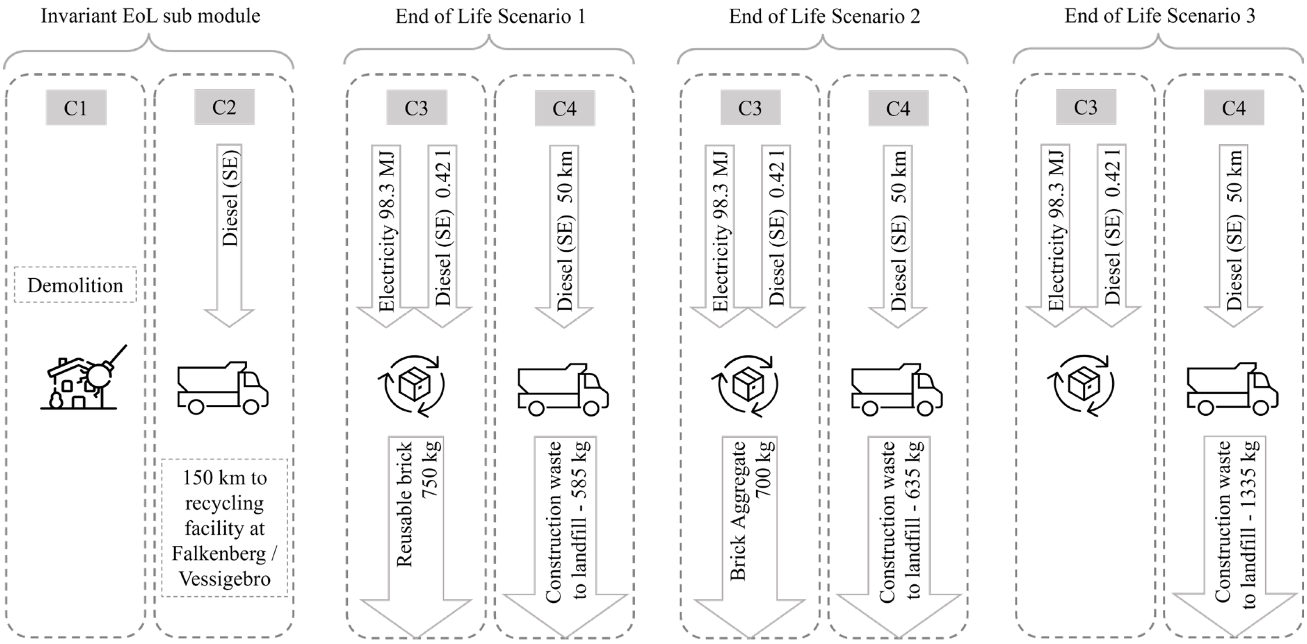

Figure 2-4 Three EoL scenarios with Inputs and outputs for reused brick

In EoL 1, 75 % of the rubble was transformed into reusable bricks, based on the average output of Brukspecialisten. In EoL 2, national scenarios were followed according to the PCR, where 70 % of the material was recycled into brick aggregate and the remaining 30 % was landfilled. EoL 3 involved the landfilling of the entire demolition waste. Although the resources required to generate different outputs may differ in reality, they were held constant in this study to enable the evaluation of the impact of solely the end product. The complete lifecycle of new and reused bricks was modelled using the two mentioned LCA software, and the plan and inputs utilised in the GaBi modelling can be found in Appendix B.

2.2.3 Environmental Impact of chosen primary fuel

To evaluate the environmental impact of the primary fuel utilised in the production stage of new bricks, the recommended energy use values presented by Boverket, as illustrated in Figure 2-5, were employed (Boverket, 2022). Greenhouse gas emissions were then computed for 1000 kg of newly manufactured façade bricks. Specifically, the chosen fuels for examination were hard coal, natural gas, wind energy-derived electricity, grid electricity, and biogas, which were selected based on the fuels used in the examined EPDs. The values presented in Boverket were in agreement with the findings reported by Oti and Kinuthia (2011) of 4189.6 MJ per 1000 kg and exhibit a high degree of correspondence with the value of 3562 MJ per 1000 kg for new bricks as reported by Zabalza Bribián et al. (2011) (Oti & Kinuthia, 2012) (Zabalza Bribián et al., 2011).

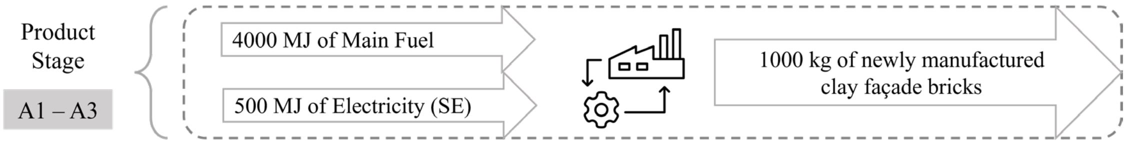

Figure 2-5 Energy inputs at the product stage as per Boverket for newly manufactured façade brick

2.3 Comparative Study and GWP Analysis of New Brick and Reused Brick Cases

With the compilation of the EPD brick database and the LCIA calculation done, the comparative study of new brick and reused brick was carried out with the following objectives:

- To compare the environmental performance of reused bricks versus new bricks in terms of their life cycle impact assessment.
- To analyse the environmental impact of EPD cases and compare them with GaBi and OpenLCA cases.
- To conduct a parametric study of the environmental impacts of different sources of energy used in the production of new bricks.
- Finally, to compare the price of newly manufactured bricks and reused bricks.

Data management was performed using Excel and statistical analysis was carried out in Python using JupyterLab (Jupyter, 2023; PSF, 2023). The Python libraries used were NumPy for handling mathematical operations and Matplotlib for plotting the data (Matplotlib, 2023; Numpy, 2023).

2.3.1 New Brick Cases

From the EPD brick database mentioned above, the life cycle impacts of GWP from lifecycle modules A, B, C and D were taken to create brick cases based on calculation principle, i.e., median or percentile, or the geographical location or the energy used for production. Since all bricks used in Sweden are imported, to create the new brick cases, EPDs considered were restricted to Denmark, Finland, Germany, and the Netherlands. It is important to note that the largest imports of bricks to Sweden come from Denmark. Additionally, Boverket's klimatdatabas conservative GWP-GHG impact values for bricks were used to create a case for comparison (Boverket, 2022). Table 2-2 provides a comprehensive summary of the brick cases that were produced using EPDs and Boverket's Klimatdatabas.

Table 2-2 New brick cases from EPDs and Boverket's Klimatdatabas

No.	Case Name	Description
1	NB_EPD_ALL_MED	The median case of new bricks made using EPDs from Denmark, Finland, Germany, and the Netherlands.
2	NB_EPD_ (DEN/FIN/GER/NLD) _MED	The median case of new bricks made using EPDs from Denmark or Finland or Germany or the Netherlands.
3	NB_EPD_ALL_MED (Green Energy Mix)	The median case of new bricks made using EPDs from Denmark, Finland, Germany, and the Netherlands which used green or renewable energy for production.
4	NB_EPD_ALL_MED (Normal Energy Mix)	The median case of new bricks made using EPDs from Denmark, Finland, Germany, and the Netherlands did not use green or renewable energy for production.
5	NB_EPD_ALL_MED (Natural Gas), (Electricity), (Biogas)	The median case of new bricks made using EPDs from Denmark, Finland, Germany, and the Netherlands which use natural gas or electricity or biogas for the production
6	NB_EPD_ALL_90%e	The 90-percentile case of new bricks made using EPDs from Denmark, Finland, Germany, and the Netherlands.
7	NB_EPD_ALL_10%e	The 10-percentile case of new bricks made using EPDs from Denmark, Finland, Germany, and the Netherlands.
8	NB_Boverket	New brick case with data from Boverket klimatdatabas.

Additionally, more new brick cases were created using data for new bricks calculated with GaBi and openLCA, as described in 2.2 are presented in Table 2-3.

Table 2-3 New brick cases from GaBi and openLCA

No.	Case Name	Description
1	NB_GABI	GaBi new brick case where A1-A3 of EPD_ALL_MED was used.
2	NB_GABI_ (Fuel Type) _MED	GaBi new brick case where A1-A3 of different fuel types were used. (Coal, Natural Gas, Wind, Electricity, Biogas)
3	NB_OLCA	OpenLCA new brick case where A1-A3 of EPD_ALL_MED was used.
4	NB_OLCA_ (Fuel Type) _MED	OpenLCA new brick case where A1-A3 of different fuel types were used. (Coal, Natural Gas, Wind, Electricity)

2.3.2 Reused Brick Cases

The methodology used for new brick cases was also applied to generate reused brick cases. Specifically, EPDs, Boverket, and LCIA calculations from GaBi and openLCA were employed for both new and reused brick cases. However, it should be noted that only one EPD from Gamle Mursten of reused bricks could be found during the EPD data accumulation. Despite its questionable validity, this EPD was considered for comparison given its exclusivity. The module D impact was calculated by using the equation as per the PCR using the virgin material substituted as the new brick and stone aggregate for EoL 1 and EoL 2, respectively. This equation and quantities considered for impact calculation can be referred to in Appendix C. Only the production stage impacts were used for calculation as it was assumed that life cycle impacts for both virgin and substituted materials would be the same. Which median A1-A3 value of EPDs was used from the brick EPDs and stone aggregate EPDs. Table 2-4 presents the analysed reused brick cases.

Table 2-4 Reused brick cases from EPD, GaBi and openLCA.

No.	Case Name	Description
1	RB_EPD (GaMur)	Reused brick case of Gamle Mursten EPD.
2	RB_BOVERKET	Reused brick case with data from Boverket klimatdatabas.
3	RB_GABI (EOL1, EOL2, EOL3)	GABI reused brick cases with different EoL scenarios.
4	RB_OLCA (EOL1, EOL2, EOL3)	OpenLCA reused brick cases with different EoL scenarios.

2.3.3 Price comparison of new and reused brick

For conducting a cost-benefit analysis of the two products, the selling price per m² of brick façade for the reused and new bricks were obtained from Brukspecialisten and Wienerberger, respectively. The costs obtained per m² of brick façade were then converted into unit values per tonne based on Boverket's suggested bulk density of 1800 kg/m³ and a wall thickness of 120 mm. The transportation distances of 640 km for the new bricks were considered consistent with Boverket klimatdatabas and reused bricks as 150 km as per Brukspecialisten data. The transportation costs for both scenarios were estimated at 0.6 SEK per tonne per kilometre. The obtained cost per new bricks ranged from 550 SEK to 2500 SEK, a value of 1050 SEK was found reasonable for a similar functioning product and the price of the reused brick price of 1000 SEK was provided by Brukspecialisten. The final landed price was determined by adding the selling price and transportation cost per tonne of bricks.

2.4 Limitation and Assumption

The study on the environmental performance of clay bricks in Europe had several limitations that were considered while interpreting the results. Firstly, the scope of the study was limited to the European region and Sweden, and the findings may not apply to other regions or types of building materials. Secondly, the study relied heavily on the accuracy and completeness of the selected brick EPDs, and any errors or missing data in EPDs might have affected the results. Additionally, the study does not consider all potential environmental impacts of brick production such as water consumption, land use, and waste categories.

Moreover, the study does not include the social and economic aspects of brick production and use, such as employment or detailed cost-benefit analysis. It is also important to note that the study assumes that the selected EPDs are representative of the entire industry, which may not always be the case. Furthermore, the study assumes that EN 15804 A2:2019 is an appropriate and reliable PCR for modelling the life cycle of both new and reused bricks.

The study also assumes that the median value of all EPDs analysed for the production stage life cycle sub-modules is an appropriate substitute for the production-specific data of the new bricks. Additionally, the study assumes that the inputs for the rest of the lifecycle modules, such as transportation and EoL scenarios, are consistent with the PCRs used. The study also assumes that the functional unit assumed (1 tonne of newly manufactured brick and 1 tonne of reused brick used in façade construction with a reference service life of 150 years) is appropriate and representative of the actual usage of bricks. Finally, the study assumes that the C2C approach is appropriate for the analysis.

In conclusion, while the study provides valuable insights into the environmental performance of clay bricks, it is important to consider its limitations when interpreting the results. These limitations highlight the need for further research for a comprehensive understanding of the environmental impact of other building materials.

2.5 Ethical Considerations

In this study, the focus is on comparing the environmental impact of new and reused bricks using EPDs. While the study cannot fully explore other ethical considerations related to the reporting of green energy or biogas in EPDs, it is important to acknowledge their existence. These considerations include the accuracy and transparency of the data used in the calculations, as well as the potential for bias or misrepresentation.

To ensure an ethical and transparent study, established calculation methods and sources of data were used, and the scope and limitations of the study were clearly defined. Additionally, the study considered the potential impact of factors such as transportation, manufacturing processes, and waste disposal on the environment.

By acknowledging and addressing these ethical considerations related to EPDs, the study aims to contribute to a more informed and responsible use of these tools in assessing the environmental impact of building materials. It is hoped that the findings of this study will provide valuable insights into the environmental impact of new and reused bricks and help to make informed decisions about sustainable building practices for years to come.

3. Results

In this chapter, the results of the EPD data analysis, LCIA conducted in LCA software and comparative analysis of reused and newly manufactured brick's environmental performance are presented. The results section is divided into three subsections: EPD analysis, parametric study, and LCIA comparison.

3.1 EPD analysis

Out of 25 European Databases, 128 valid EPDs were collected in the early-stage EPD compilation as described in the method. From the 128 valid EPDs, 147 distinct EPDs were identified for analysis as some EPDs reported up to three, related yet separately manufactured products under a single declaration, compelling the extraction of separate datasets for each product represented. The final EPD brick database for analysis consists of 147 distinct EPD. The EPD analysis section includes the results of 147 EPD collected. The obtained EPDs were filtered based on the data quality used, PCR and CPCR adopted, EoL scenarios considered, and energy used for manufacturing. Finally, the GWP values of the sorted EPDs were collected for analysis.

3.1.1 EPD collection results

A total of 128 valid EPDs of clay products were collected initially, regardless of functional units. 50 % of the EPDs originated from EPD Denmark, where the program operator was the Danish Technological Institute, followed by France with 18 % of the EPDs, Germany with 8 % and Spain with 6 % and so on, as depicted in Figure 3-1. Sweden contributed a meagre 2 EPDs, with 4 data points, aligning with Boverket's claim of non-existent new brick manufacturing plants in Sweden.

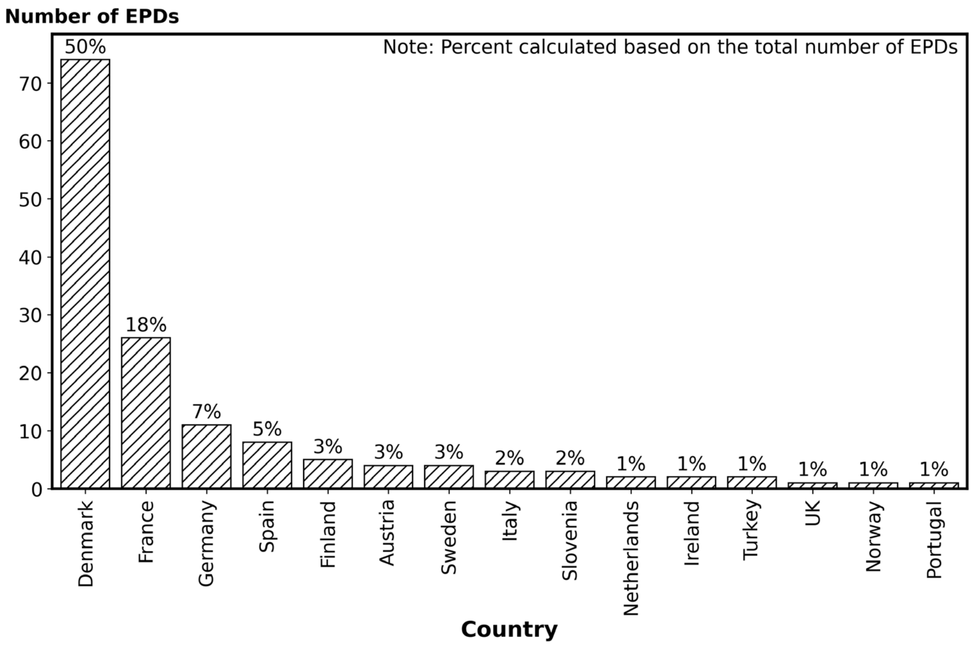

Figure 3-1 Number of EPDs based on country of origin together with the share of the total in per cent.

However, the initial database also contained limited quantities of EPDs on clay tiles, clay pavers, doubled-fired bricks, brick with insulation and calcium silicate units shown in Figure 3-2 (left) which were omitted from further analysis. Subsequently, only 126 out of 147 EPDs related to bricks were chosen. As previously mentioned, the search yielded only two EPDs for reused bricks; however, one of which related to a new façade system incorporating reused brick was also omitted as it did not offer any relevant data for the research.

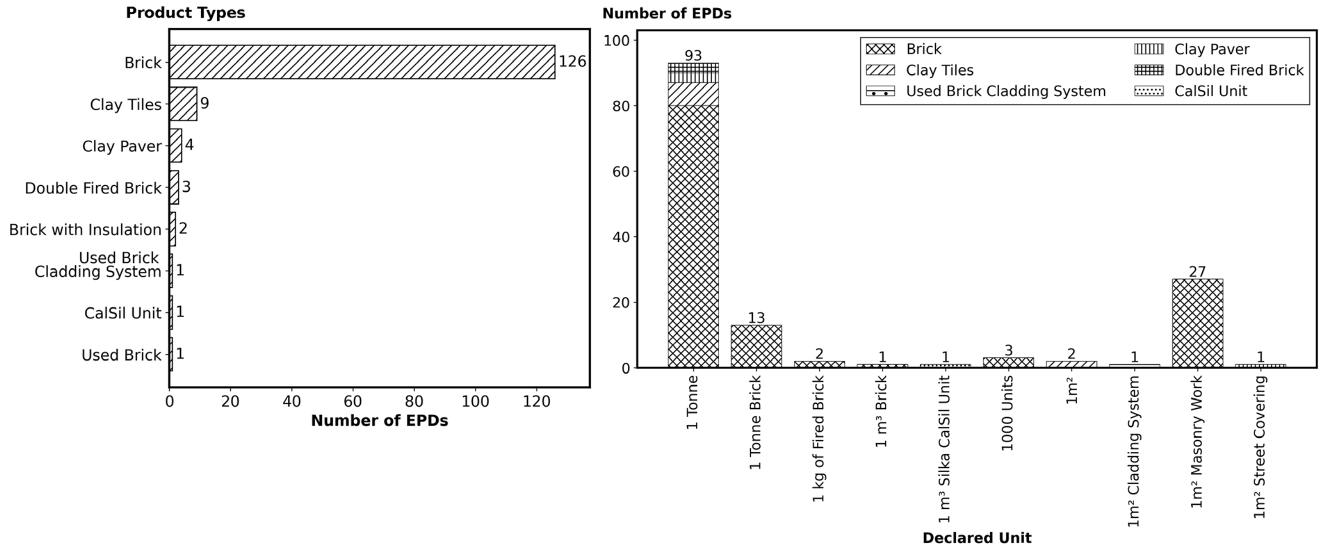

Figure 3-2 Number of EPD based on Product Type (Left) and Declared Unit (Right)

Multiple declared units were used in the studied EPDs, with '1 Tonne' and '1 Tonne Brick' being the most frequent, featured in over 100 EPDs. The second most commonly used declared unit was '1 m² Masonry Work', with 27 EPDs as shown in Figure 3-2 (right).

3.1.2 PCR and CPCR usage analysis

Although EN15804 A2:2019, a general PCR, was implemented in 2019, it only accounted for 10 % of the EPDs. In contrast, EN15804 A1:2013, established in 2013, accounted for 81 % of EPDs. EN15804 A1:2014 was responsible for 8 % of EPDs, and 2 % of EPDs did not specify the PCR used as shown in Figure 3-3 (left). Regarding the specific PCR for bricks presented in Figure 3-3 (right), the TBE PCR, established by Tiles Brick and Europe, was utilised in 56 % of EPDs. Country-specific PCR (CPCR) constituted the remainder of EPDs, with France's NFEN15804/CN being employed in 20 % of EPDs and Spain's GloablEPD-PCR-008 in 4 % of EPDs.

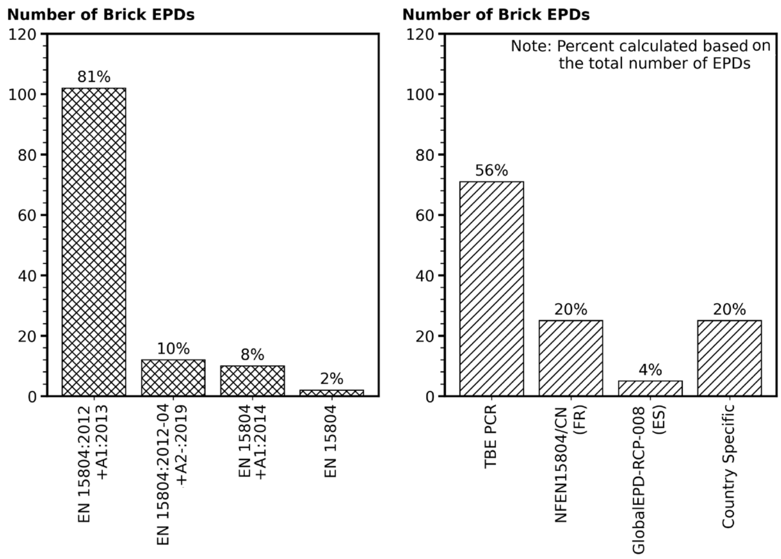

Figure 3-3 Product Category Rules Distribution – PCR (left) and CPCR (right)

3.1.3 EPD quality analysis

Regarding the primary LCI data utilised for the brick EPDs, it can be noted that the majority of the flows from brick factories were sourced from recent years. Specifically, the year 2020 and 2019 data were the most frequently referred to, accounting for 35 % and 30 % of the brick EPDs, respectively. Because of the up-to-date data, the EPD quality was ascertained to be satisfactory for further analysis. It is worth noting that older data from 2011 was only utilised in a small percentage of EPDs, constituting a meagre 2% as shown in Figure 3-4.

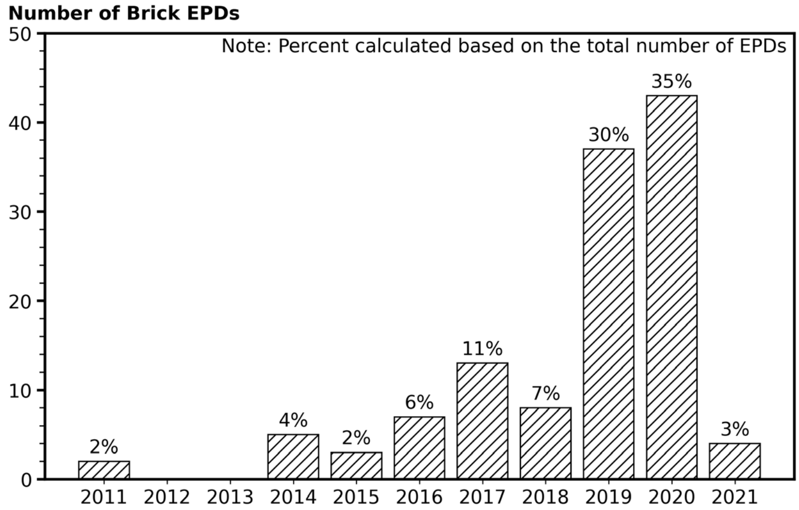

Figure 3-4 Specific Primary LCI Data Time of Collection

Figure 3-5 illustrates the secondary LCI datasets used to evaluate the impact of secondary input data, such as transportation and waste, which were procured from diverse databases. It can be noted that Ecoinvent and GaBi emerged as the most prevalent sources, albeit in varying versions. Particularly, Ecoinvent 3.5 was identified as the most utilised dataset, featuring 40 % of EPDs.

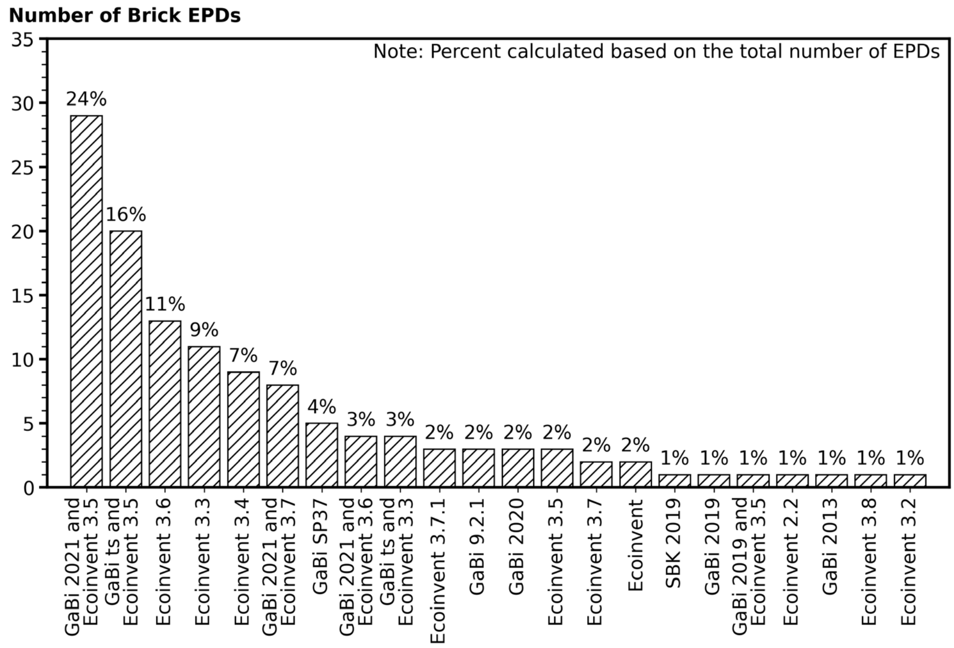

Figure 3-5 Secondary LCI Datasets Usage

Regardless of the type of PCR utilised, it was observed that a total of 26 % of the EPDs across different PCR declared the impacts of raw material supply, transport, and manufacturing separately in the A1 to A3 modules.

Furthermore, over 70 % of the EPDs did not provide separate declarations for these categories as presented in Figure 3-6.

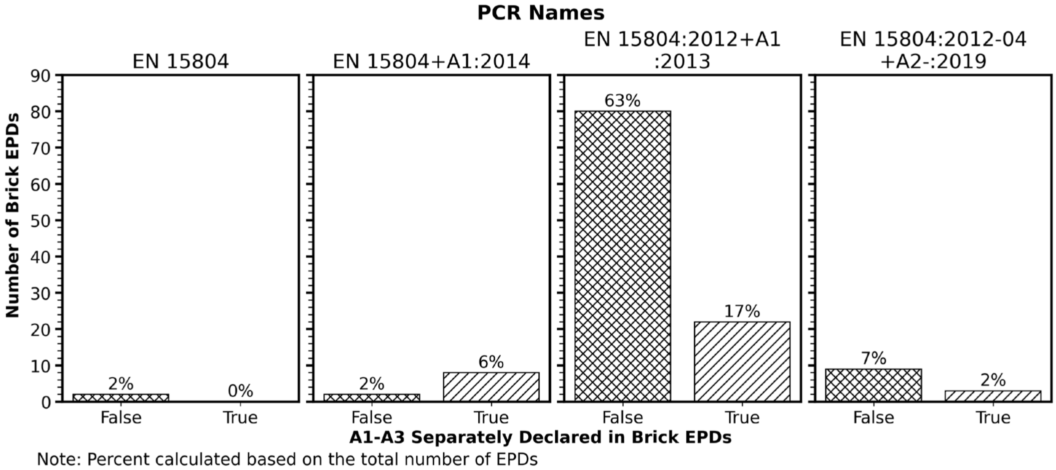

Figure 3-6 A1 to A3 Modules Separately Declared

Regarding impact allocation, only 28 % of the EPDs across all the CPCRs used allocations, while the remaining 72 % did not, as shown in Figure 3-7. This reinforced the analysis conducted subsequently. It is important to highlight that none of the EPDs that employed the TBE PCR mentioned utilising allocation. This reason for not mentioning allocation was further investigated and found that it was justified as many EPDs needed to allocate the annual output of one or even multiple factories as per the TBE PCR.

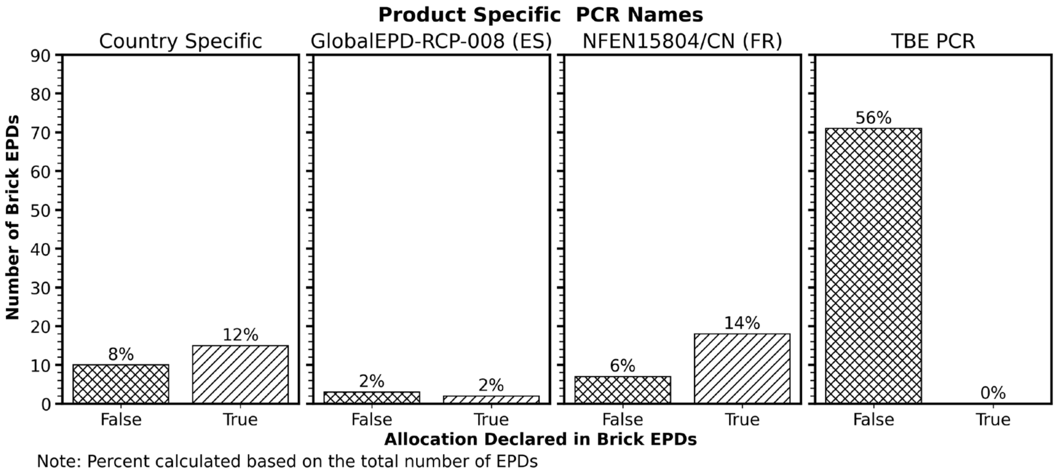

Figure 3-7 Allocation Declared

Cut-off criterion was a critical aspect of LCA methodology, as they enable the exclusion of trivial inputs and outputs that do not significantly affect the overall environmental impact of the product. An interesting observation is that all EPDs that utilised the TBE PCR method employed cut-off criteria for input and output flows of energy use and mass, while a mere 24 % of the EPDs did not declare or mention the utilisation of any criterion as presented in Figure 3-8. This resulted in a more focused and accurate analysis of the product's lifecycle.

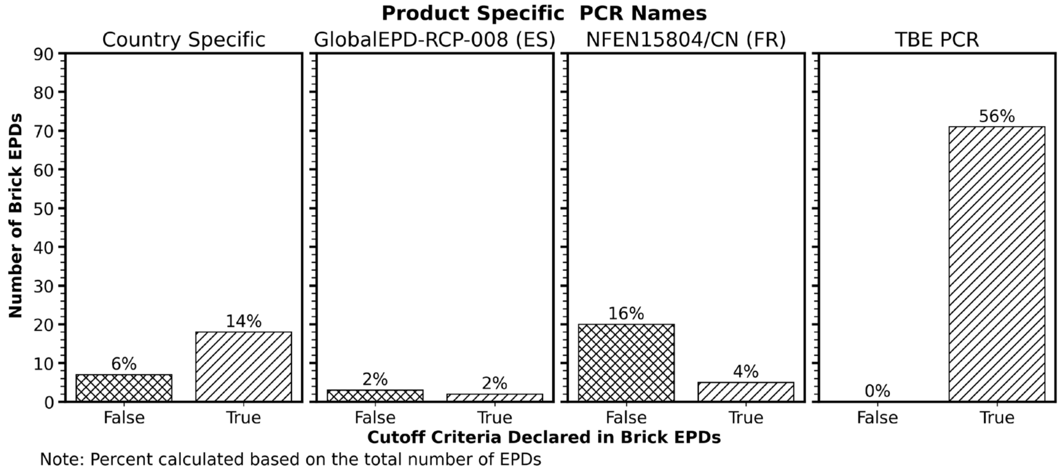

Figure 3-8 Cut-off Criteria Declared in EPDs

From Figure 3-9 (left), it can be noted that the transport distance to the construction site from the factory gate utilised was mostly 50 km, but a few reported distances as high as 250 km. Likewise, the transport distance to waste processing was declared as 50 km by around 30 EPDs, as illustrated in Figure 3-9 (right). However, it is important to understand that these distances mainly reflect the country-specific scenarios adopted to produce these EPDs as per the adopted PCRs.

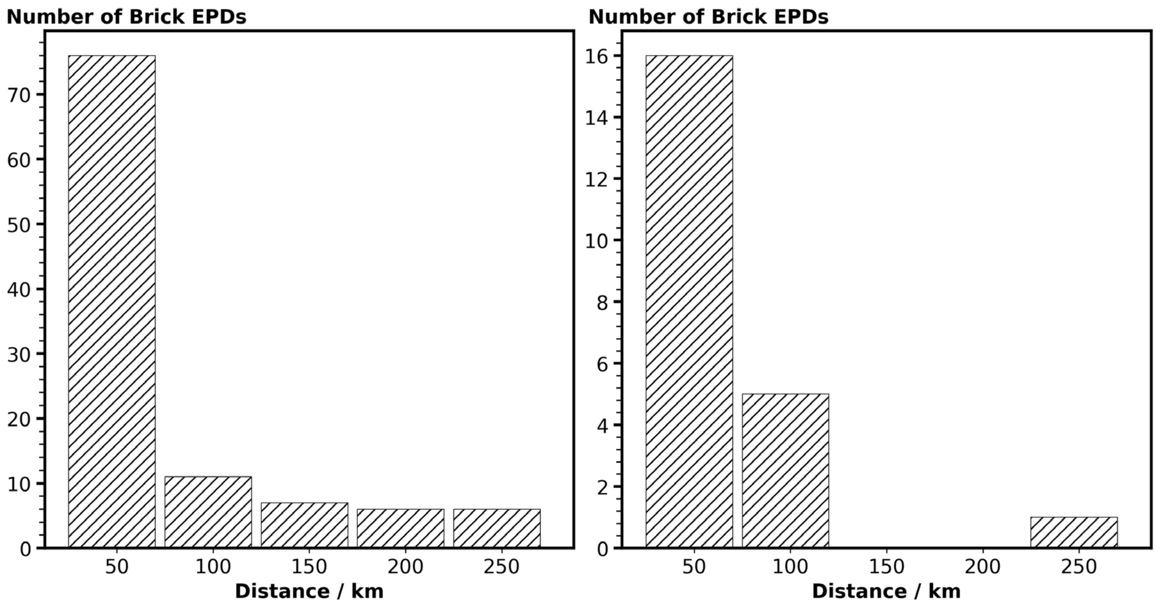

Figure 3-9 Transport Distance in Brick EPD - A4 (left) and C2 (right)

About half of the brick EPDs declared Module C1, which refers to the impacts resulting from the destruction of bricks at the end of their life cycle, as presented in Figure 3-10. The remaining EPDs did not declare Module C1, citing reasons such as the rules of CPCR or the impacts of removing a brick from a structure are assumed to be allocated to the entire structure, and any impacts allocated solely to the brick are considered negligible and treated as zero.

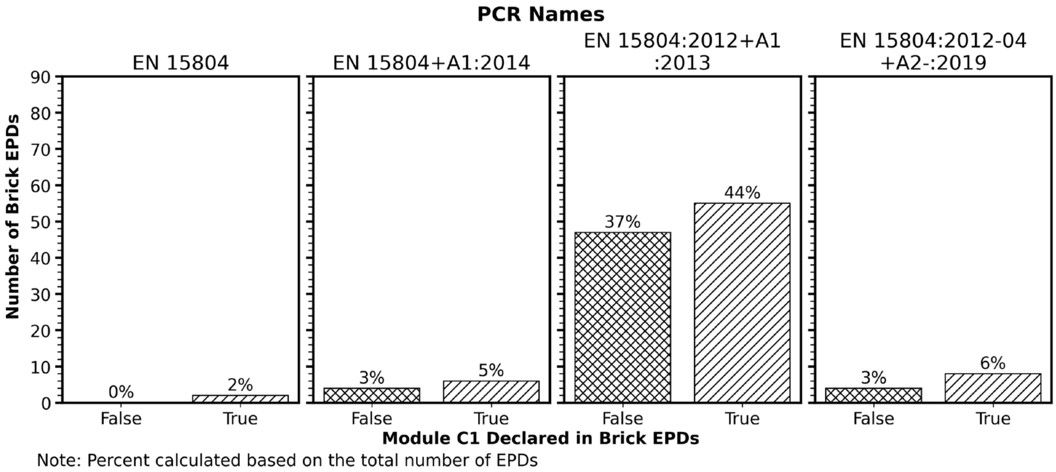

Figure 3-10 Module C1 Declared and PCR used

3.1.4 New brick EPD EoL (EoL) scenarios analysis

Figure 3-11 presents a box plot of various EoL scenarios for new brick EPDs, which were typically declared in percentage. Notably, none of the EPDs had accounted for EoL scenario 1, where the bricks were cleaned and reused. Instead, most new bricks were crushed into smaller aggregates and reused either on-site or sent off-site, resulting in a median of 99 % for EoL scenario 2. The remaining waste from EoL scenario 2 was sent to the landfill in EoL scenario 3, which had a median of 1 %. Thus, by combining scenarios 2 and 3, most of the brick's EoL outcomes were covered.

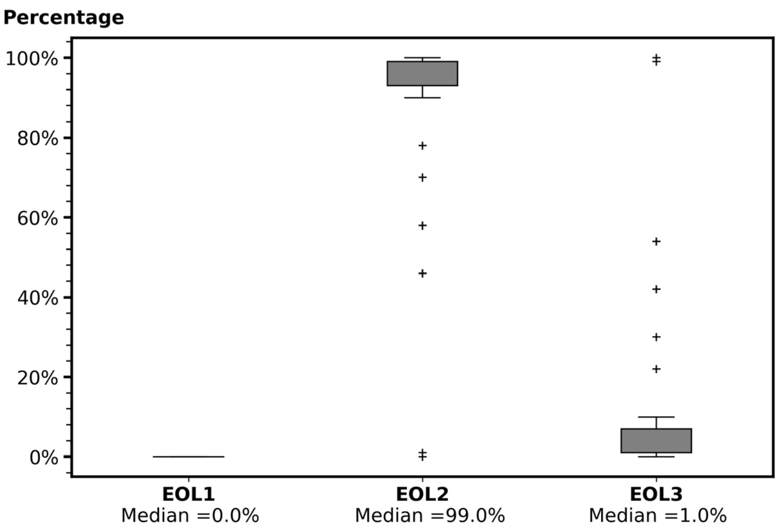

Figure 3-11 Boxplot of EoL Percentage

3.1.5 New brick EPD energy usage analysis

In the production stage of brick manufacturing, numerous primary fuels were employed, with biogas being the most frequently declared fuel type, accounting for 22 EPDs. While natural gas was primarily used for the kiln and electricity, secondary energy sources such as green electricity and biomass were also utilised as presented in Figure 3-12. Notably, the analysis revealed a significant trend towards the utilisation of green or renewable energy, with 63 % of new brick productions employing such sources. Moreover, the analysis revealed that the utilisation of renewable energy sources in brick manufacturing was not limited to a single type of renewable energy. Instead, a diverse range of renewable energy sources was employed, including biogas, electricity from wind power, and bio-natural gas.

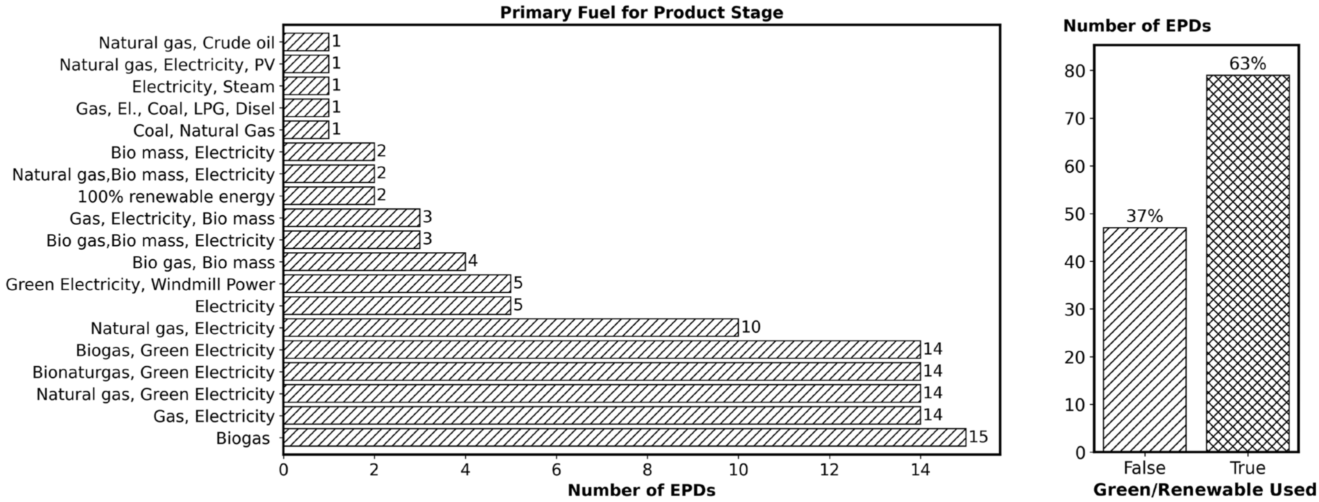

Figure 3-12 Primary Fuel for Product Stage (left) and Green/Renewable Used in Production (right)

3.1.6 GWP analysis

The analysis of the GWP impacts of EPDs was conducted initially to provide an overall perspective. Subsequently, a case study utilising median values was created to analyse the impact of EPDs on newly manufactured bricks.

3.1.6.1 Overall new brick EPD analysis

As outlined in the methodology, Figure 3-13 represents the total GWP impacts of all the new brick EPDs from Denmark, Finland, Germany, and the Netherlands. The analysis revealed that the upper bound of the impacts was 3.5E+02 $kgCO_2eq./t$, while the lower bound was 6.3E+01 $kgCO_2eq./t$. The central tendency of the data, represented by the median impact or 50th percentile, was approximately 1.6E+02 $kgCO_2eq./t$. Notably, the graph had proven the absence of any extreme outliers, as the 10th and 90th percentiles corresponded with expected values.

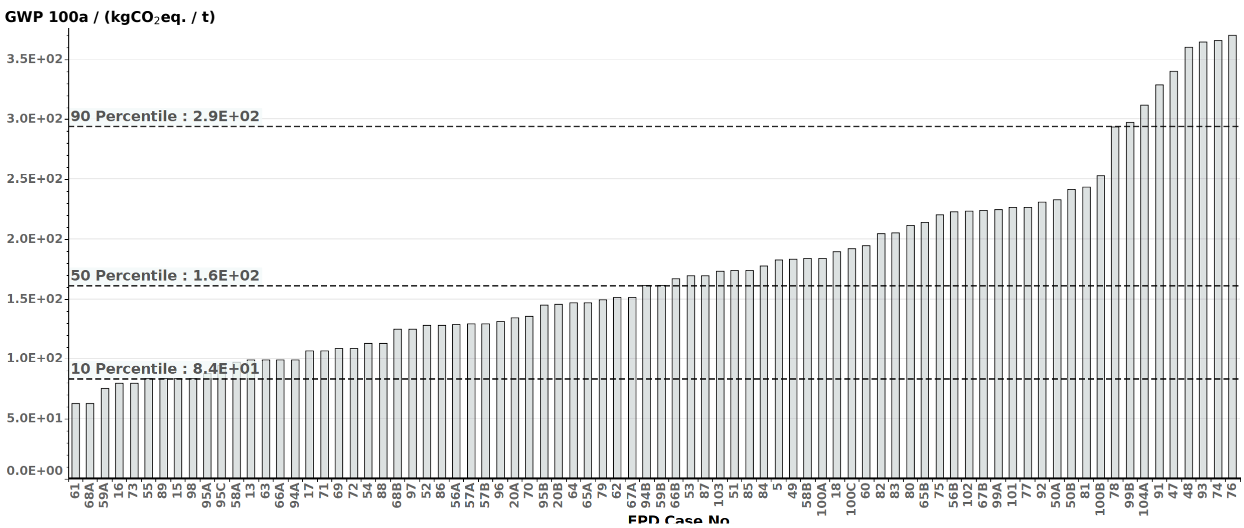

Figure 3-13 Percentile Area Graph of GWP Total of Brick EPDs

3.1.6.2 EPD new brick cases analysis

The analysis showed that Germany had the lowest median GWP total in $kgCO_2eq./t$ among the countries studied, with 1.1E+02. Following closely were Denmark and the Netherlands, with 1.6E+02 and 1.8E+02, respectively. The highest median GWP total was observed in Finland, with 3.1E+02. It can be noted that while the impacts from A1 to A3 modules had a relatively narrow range, from 9.9E+01 to 1.8E+02, the A4 to A5 modules showed a wider range of 6.5E+00 to 1.2E+02, as depicted in Figure 3-14.

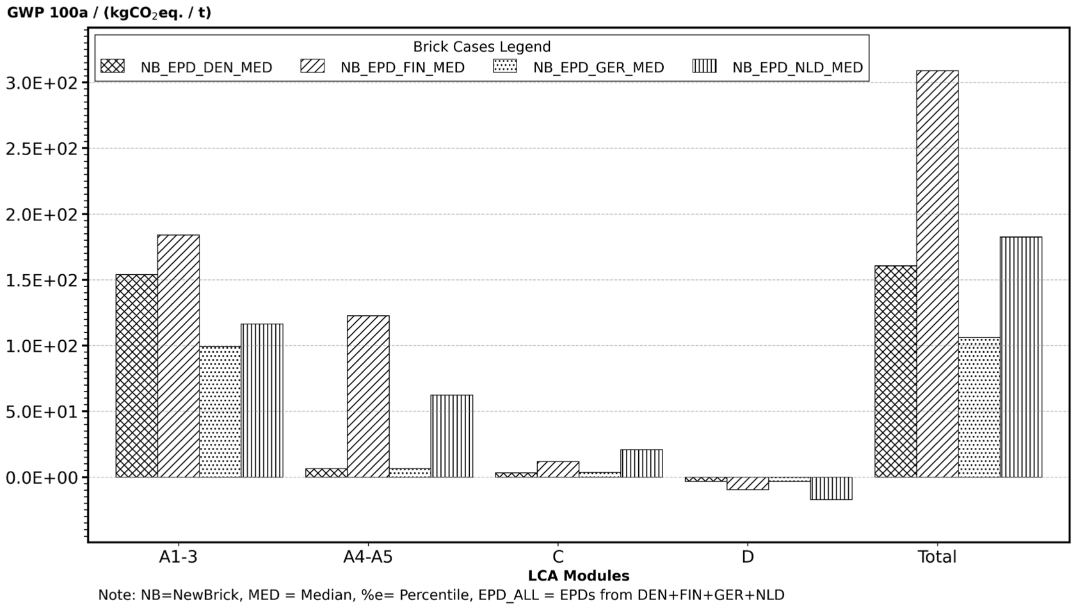

Figure 3-14 Impact Analysis (GWP) of Brick EPD Cases by Country

In terms of energy use during production, the results were as expected. The standard energy mix, consisting of hard coal, coke, diesel, and natural gas, had the highest GWP impact of 2.2E02 $kgCO_2eq./t$, as depicted in Figure 3-15. Unlike the country-specific cases, the A1-A3 modules had the most significant impact on the total. Notably, bricks manufactured solely using electricity had the least impact, with only 1.1E+02 $kgCO_2eq./t$. It can be noted that the difference in impact using natural gas and biogas was insignificant.

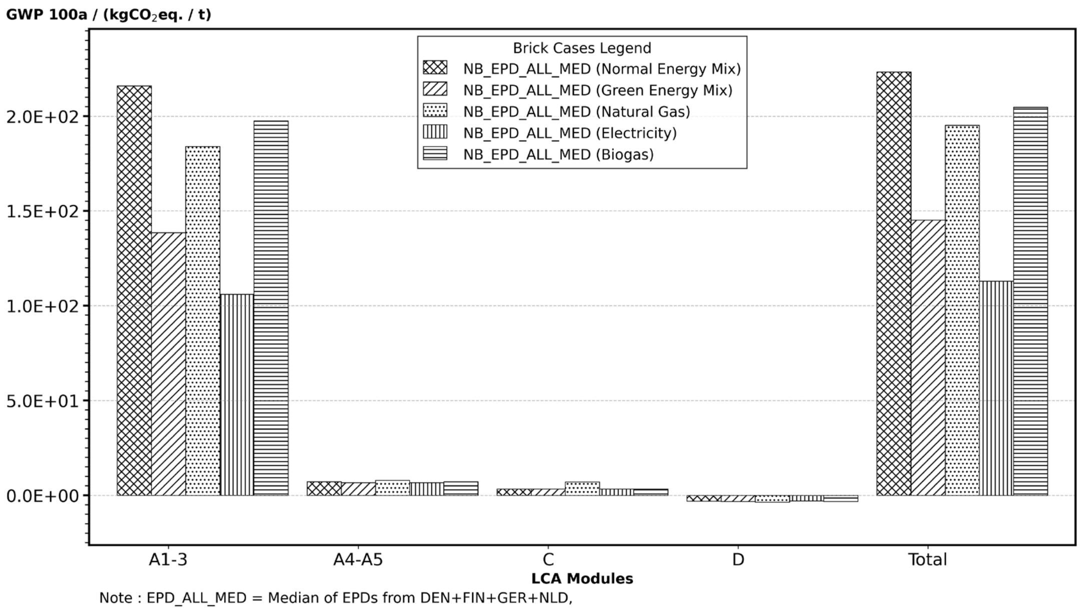

Figure 3-15 Impact Analysis of Brick EPD Cases by Energy Used for Production

3.2 Lifecycle Impact Assessment (LCIA) using openLCA and GaBi ts

The life cycle impact assessment using OpenLCA and GABI ts is divided into three sections: LCIA results of new brick, reused brick, and energy sensitivity analysis.

3.2.1 LCIA result of new brick

Comparative analysis results of the GWP100a impacts of the cases for new brick from EPDs, Boverket's, GaBi, and openLCA are presented in Figure 3-16. The A1-A3 modules for GaBi and openLCA were identical to those in EPDs, as stated in the methodology. However, for A4-A5 modules, the values varied, with Boverket having the highest value of 6.8E+01 kgCO_2eq./t, followed by GaBi and openLCA with 3.7E+01 kgCO_2eq./t and 3.2E+01 kgCO_2eq./t, respectively. Notably, Boverket only provided data for A1-A3 modules. For the C module, EPDs had the lowest value of 3.3E+00 kgCO_2eq./t, while GaBi had 1.3E+01 kgCO_2eq./t, and openLCA had the highest value of 8.3E+01 kgCO_2eq./t. For the D module, EPD had the least negative value of -3.2E+00 kgCO_2eq./t, while both GaBi and openLCA had a more negative value of -8.8E+01 kgCO_2eq./t. The results revealed that Boverket had the highest values overall, followed by EPDs, GaBi, and openLCA in that order.

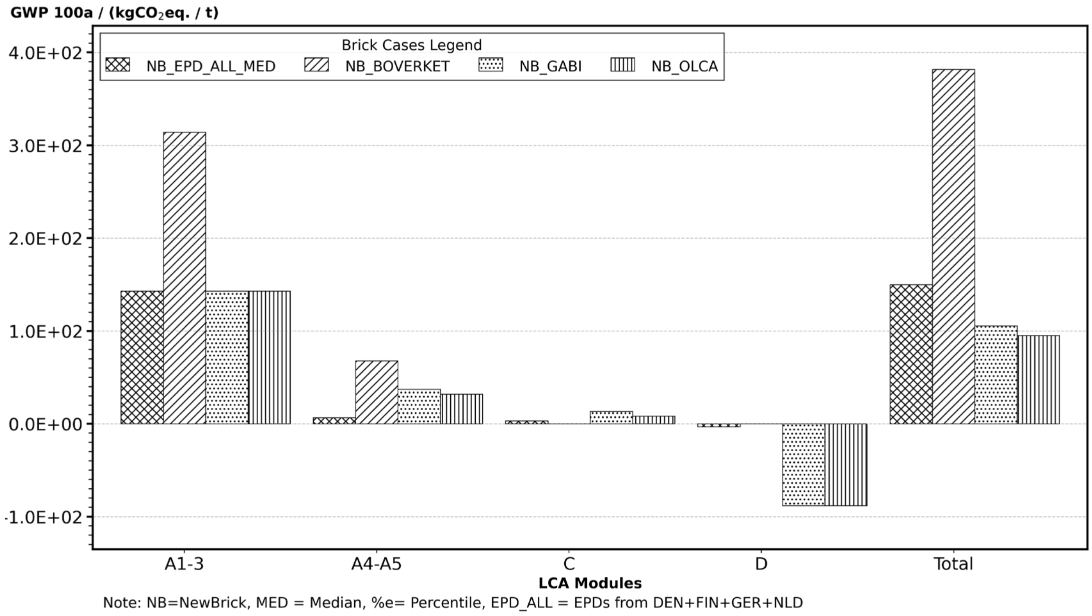

Figure 3-16 Brick Cases Analysis - EPD vs Boverket vs GaBi vs openLCA

3.2.2 LCIA results of reused brick

3.2.2.1 Reused brick case results

Reused brick cases presented in Figure 3-17 compared the GWP100a impacts of Gamle Mursten's reused brick EPD and Boverket's reused brick case against reused brick LCIA results of GaBi and openLCA. Gamle Mursten's reused brick EPDs only declared A1-A3 modules, yielding a value of 2.7E+01 kgCO_2eq./t. This is the second lowest among all the cases where Boverket declared no product stage impact for reused bricks. Boverket only published A4-A5 modules, with a value of 4.5E+00 kgCO_2eq./t which was the second lowest overall. GaBi had the highest value in all modules with a total of 7.6E+01 kgCO_2eq./t as opposed to openLCA's

5.1 E+01 $kgCO_2eq./t$. It is worth mentioning that the comparison was made using EoL scenario 2, which involves crushing bricks to aggregate, as it was the most prevalent scenario among EPDs.

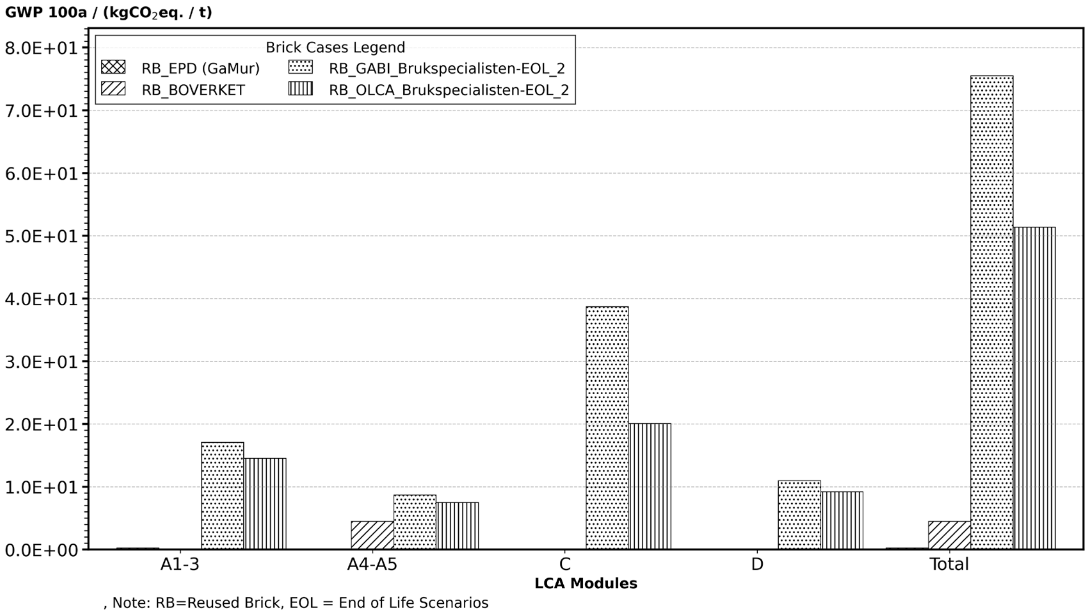

Figure 3-17 Reused Brick Case Analysis - EPD vs Boverket vs GaBi(EoL-2) vs openLCA(EoL-2)

3.2.2.2 EoL results

As anticipated, EoL 1, bricks are cleaned and reused, yielded the least GWP100a results compared to EoL 2, where the bricks are crushed into aggregates, and EoL 3, where all bricks are landfilled as presented in Figure 3-18. The GaBi LCIA and openLCA both yielded negative results, with -9.4E+01 $kgCO_2eq./t$ and -9.6E+01 $kgCO_2eq./t$, respectively, for module D in EoL 1. Notably, the C2 module in openLCA had significantly lower impacts compared to GaBi, with values of around 5.3E-02 $kgCO_2eq./t$ and 1.6E+01 $kgCO_2eq./t$, respectively. EoL 3 had the highest overall impacts, with no impacts reported for module D. It is important to highlight that both GaBi and openLCA reported positive impacts for module D in EoL 2, presumably due to the lower impacts of the substituted virgin material, stone aggregate.

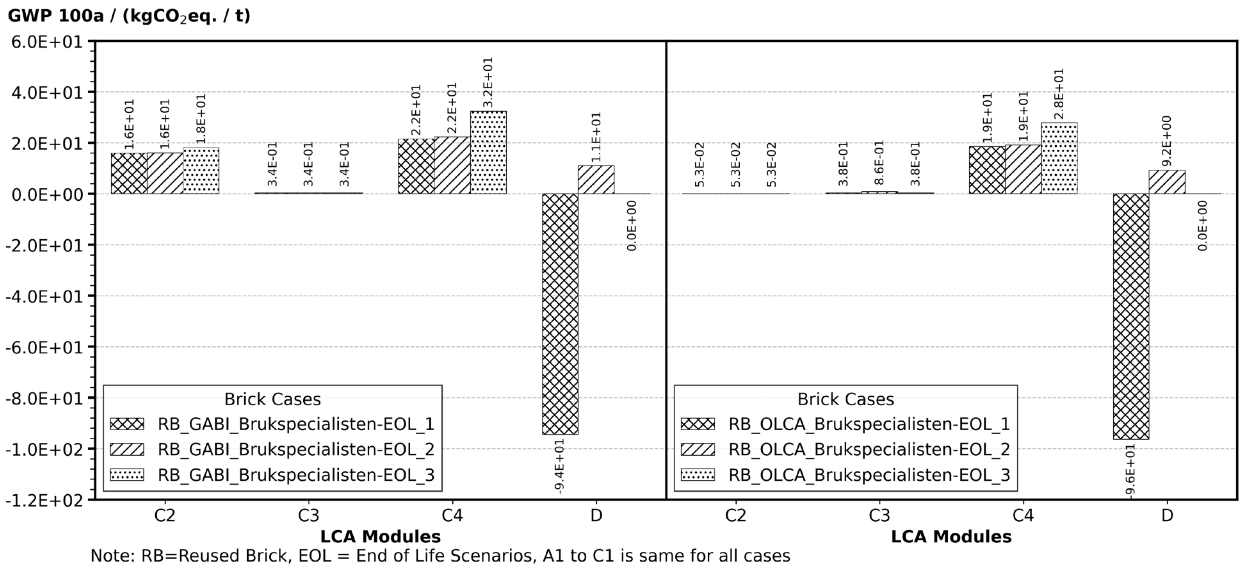

Figure 3-18 EoL Scenario Analysis - GaBi (left) and openLCA(right)

3.2.3 LCIA result of energy sensitivity analysis

The sensitivity analysis for different primary energy sources used in the product stage calculated in GaBi and openLCA is presented in Figure 3-19 and Figure 3-20, respectively. Only A1-A3 and D modules were presented for comparison as the other module impacts remained the same. In Gabi's LCIA results, Hard coal had the greatest impact of 1.0E+03 kgCO_2eq./t in A1-A3, with the lowest impact in module D of -7.2E+02 kgCO_2eq./t. The total impact of coal was 3.7E+02 kgCO_2eq./t. Natural gas, biogas, and the Swedish electricity mix followed coal in terms of impact, while electricity from wind power had the lowest impact of 6.7E+01 kgCO_2eq./t.

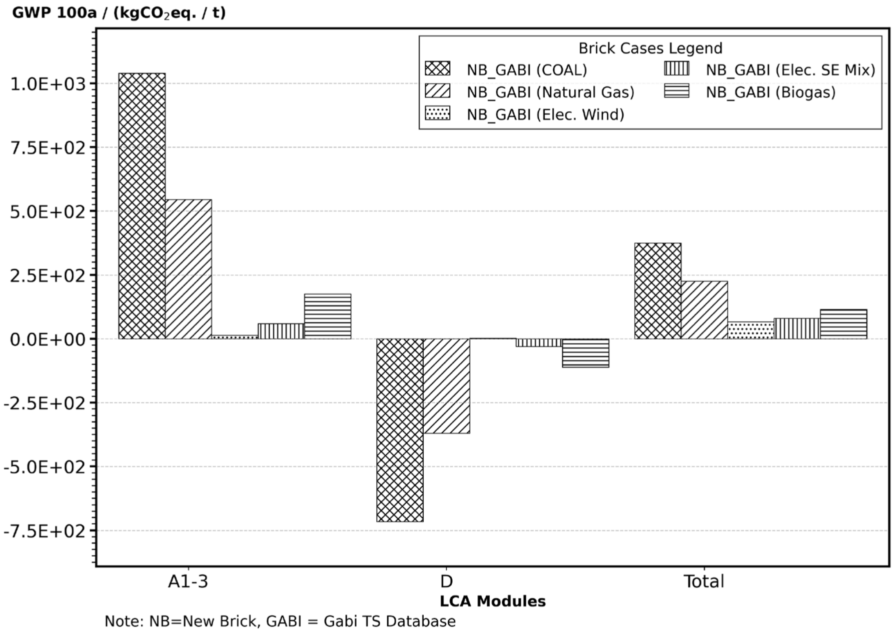

Figure 3-19 Primary Energy Sensitivity Analysis - GaBi

In contrast to GaBi, openLCA's highest GWP100a impacts from the Swedish electricity mix was 7.2E+01 kgCO_2eq./t, followed by Hard coal, natural gas, and electricity with wind power. It can be noted that the energy used during the production stage directly impacts the potential benefits of reuse and recovery.

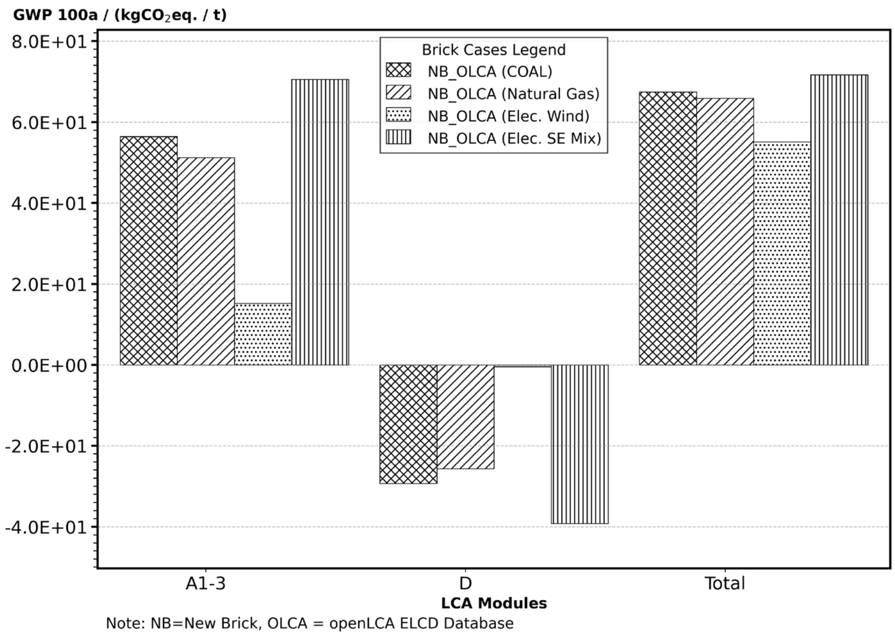

Figure 3-20 Primary Energy Sensitivity Analysis – openLCA

3.3 Price comparison of new and reused brick

The results of the cost-benefit analysis of the two products are presented in Table 3-1, although the selling cost at the factory gate per m² of brick was very similar, the associated transportation costs determined the financial feasibility, for the values chosen, reused bricks would be economically beneficial. However, a more detailed cost-benefit analysis with other associated costs like installation, loading costs and material wastage that were not included would improve the accuracy.

Table 3-1 Landing price comparison of new and reused bricks

	Distance (A4)/(km)	Transportation cost/ (SEK/(t · km))	Selling Price per m²/(SEK/m²)	Selling Price per tonne/(SEK/t)	Final landing cost/(SEK/t)
New Brick	640	0.6	1050	5093	5477
Reused brick	150	0.6	1000	4630	4720

3.4 Comparative Study of brick cases

This chapter presents the comparative analysis wherein the median values of EPDs were compared against the new brick cases, reused brick cases, and cases using different primary energy sources. The results are presented through normalisation with the median GWP of EPDs (shown in red) as the reference value.

3.4.1.1 EPD median vs new brick cases

The comparative study of the new brick cases against the median case of EPDs is presented in Figure 3-21. It can be observed that the GWP of the new brick in Boverket's klimatdatabas case was more than 2.5 times higher than the EPD median case. However, values calculated in GaBi and openLCA were close to the EPD median.

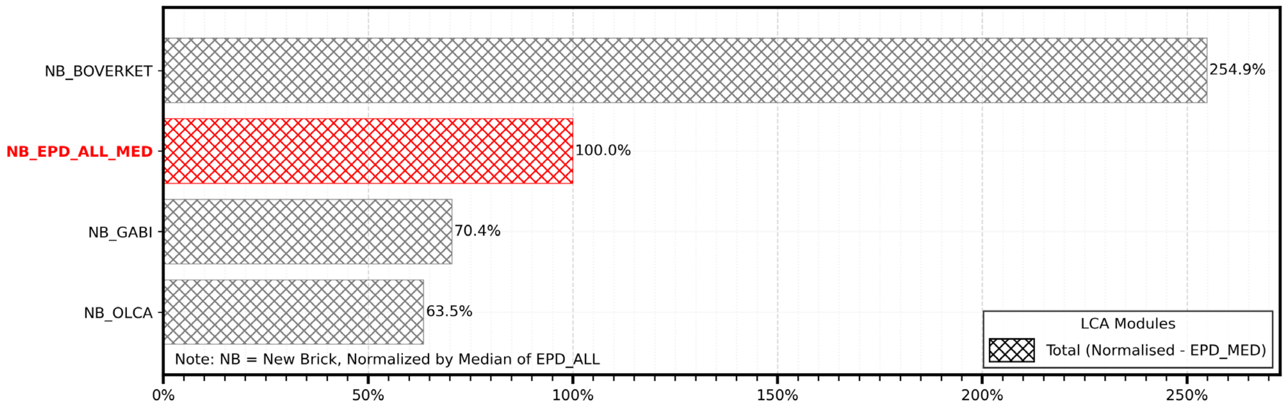

Figure 3-21 New Brick Cases Analysis – Normalised

3.4.1.2 EPD median vs reused brick cases

The comparative study of the reused brick cases against the EPD median case is shown in Figure 3-22. The GWP impact of all reused brick cases is considerably less than the median EPD value with GaBi providing slightly higher values than openLCA. EoL 1 values were found to be the lowest followed by EoL 2 and EoL 3 in that order. Boverket values for reused bricks were significantly lower than the calculated values except for the EoL 1 cases, proving that reclaiming bricks at EoL would be the best solution for lowering carbon emissions.

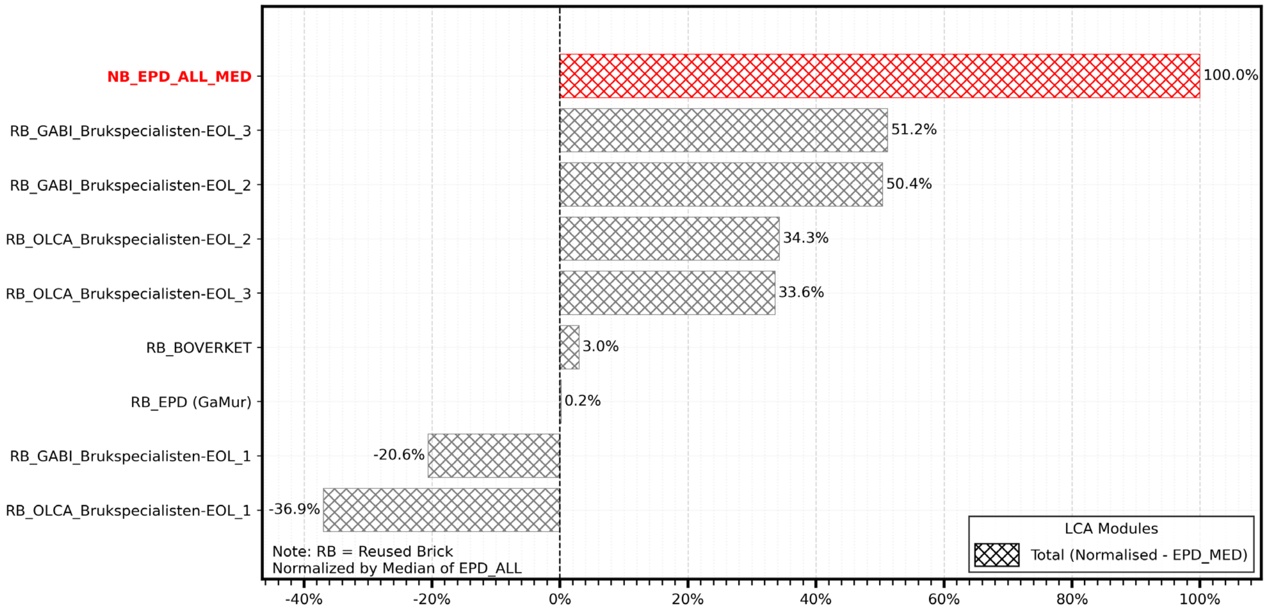

Figure 3-22 Reused Brick Cases Analysis - Normalised

3.4.1.3 EPD median vs energy cases for newly manufactured brick

The comparative study of the cases using different primary energy sources cases against the EPD median case is shown in Figure 3-23. As expected, the GWP value of coal as fuel with 250 % was the highest and cases using electrical energy from wind power had the least and negative impact compared to the EPD median value. Moreover, the cases obtained from the EPDs presented higher GWP values except for the top two GaBi cases.

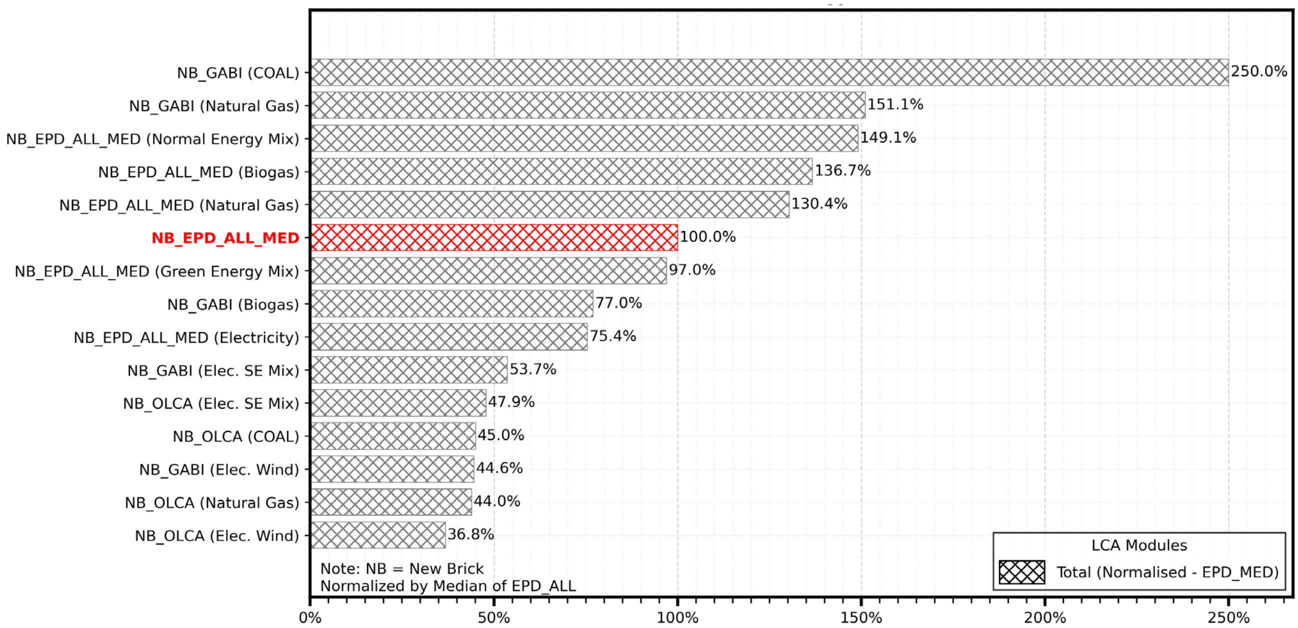

Figure 3-23 Energy Cases Analysis - Normalised

4. Discussion

The brick industry is a significant contributor to GHG emissions and the depletion of natural resources (Koroneos & Dompros, 2007) and brick production also has a large impact on energy use and carbon emissions (Buchanan & Honey, 1994; Koomey et al., 1998; Oka et al., 1993). In light of this, there is a growing demand for sustainable building materials, and the circular economy is increasingly being viewed as a way to reduce the environmental impact of the brick industry (Ncube et al., 2021; Ottosen et al., 2021). This study aimed to compare the environmental performance of new and reused bricks in terms of their lifecycle GWP impact and evaluate the accuracy of EPDs for bricks. Additionally, a parametric study of the environmental impacts of different sources of energy used in the production of new bricks was conducted.

EPD analysis discussion

EPDs are an important tool for assessing the environmental impact of building materials (Rezaei et al., 2019). However, to ensure that EPDs are comparable and provide accurate information, certain criteria must be met. As noted by Gelowitz (2017), for EPDs to be comparable, the functional or the declared unit used should be the same or convertible. Moreover, they should also consist of the same impact categories with identical system boundaries or coordinating lifecycle sub-modules reported separately. Additionally, they should have been made following the standardised guidelines of ISO 14025 and identical cut-off rules (Gelowitz & McArthur, 2017).

The study collected data from 128 valid EPDs from various European POs. Denmark contributed the highest number of EPDs, followed by France, Germany, and Spain. However, Sweden contributed only two EPDs, indicating a lack of new brick manufacturing plants in the country (Boverket, 2020, 2022). The collected EPDs were based on harmonised standards, such as EN 15942, EN15804 and TBE PCR, making them comparable and considered for further evaluation (Minkov et al., 2015).

The study assessed the accuracy of the EPDs and discovered that a significant number of them (around 75%) lacked separate declarations for product stage sub-modules, namely, raw material supply, transport, and manufacturing. These declarations are necessary for a comprehensive LCIA, as the Product stage has the highest impact across all modules (Almeida et al., 2015). To elaborate, the firing of clay requires a considerable amount of energy to maintain the temperature (Koroneos & Dompros, 2007). This process also releases CO_2 trapped in the clay, which averages 0.41 kg CO_2 per brick (Lourenço & Vasconcelos, 2015). To further enhance the accuracy of the assessment, the raw material supply module (A1), which involves excavating topsoil and potentially releasing trapped carbon (even if in small amounts and with cut-off criteria), should be clearly defined (Nath et al., 2021). Furthermore, it is necessary to account for the loading and transport operations, despite the common occurrence of clay pits being located near the factory (Bovea et al., 2007). Furthermore, only about half of the brick EPDs declared Module C1, which refers to the impacts resulting from the deconstruction of brick facades at the EoL stage. The results of the study demonstrated that the unit '1 tonne' was the most commonly used, indicating that its universal implementation across all EPDs would be advantageous.

The high recycling potential of bricks from a building, estimated at approximately 80% according to Papadaki (2022), enabled their reuse in various applications (Papadaki et al., 2022). However, none of the EPDs examined accounted for the EoL scenario 1, which involves cleaning and reusing the bricks, despite its potential environmental benefits. But it is important to acknowledge that most of the EPDs analysed favoured EoL scenario 2, in which the bricks are crushed and reused.

With regards to impact allocation and cut-off criteria, it is worth noting that a meagre 28 % of the EPDs employed allocations, while the vast majority (72 %) either lacked information or refrained from utilising such methods. Furthermore, 24 % of the EPDs did not declare or acknowledge their use of cut-off criteria. These results align with the observations made by Moré et al (2022), where nearly half (46 %) of the EPDs examined were found to be deficient in their information regarding cut-off rules and allocations (Moré et al., 2022).

The majority of the LCI flows from brick factories were sourced from recent years, with the years 2020 and 2019 data being prominent and frequently referred to. This inclusion of the recent primary data as part of the LCI was deemed highly advantageous and ensured the data quality (Kinuthia et al., 2018). The secondary LCI dataset sources often used were Ecoinvent and GaBi databases. Although the use of Ecoinvent and Gabi databases were considered industry standards, there could be possible deviations and incorrect flows used in LCIA calculations due to the range of values obtained from EPD data (Pauer et al., 2020). Therefore, the study recommends that manufacturers provide more detailed and comprehensive declarations in their EPDs to ensure an accurate and wholesome lifecycle assessment of their products.

Additionally, the study evaluated the environmental impact of new and reused bricks in terms of their GWP. The study found that the highest GWP100a impact was associated with the standard energy mix which includes a mix of fossil fuels such as coal, natural gas, and oil, while the least impact was associated with bricks manufactured solely using electricity from wind power. Furthermore, the analysis showed that there was a significant trend towards the utilisation of green or renewable energy in new brick production, with such sources being employed in 63 % of new brick productions as shown by the results and are needed in the industry to move towards resource efficiency and reduce environmental load (Prasertsan & Theppaya, 2007; Yüksek et al., 2020). Especially in Denmark, where 55 % of the new brick EPDs claimed to use biogas. However, given that the findings are based on the EPD documents alone, a deeper examination of this claim can be investigated as according to Weihe et al. (2022), as mentioned in the Danish government's green gas strategy, biogas only accounted for approximately 20 % of the Danish gas consumption in 2021 (Danish Ministry of Climate, 2021; Johan Weihe et al., 2022)

Overall, the EPD study provided valuable insights into the environmental impacts of new brick production in Europe and highlights the need for more comprehensive and standardised approaches in EPDs to better assess the environmental performance of building materials. Furthermore, this observation applies to the reuse of bricks and other circular materials, as the industry necessitates a systematic approach to documenting the quality of these reused materials (Araujo Galvão et al., 2018; Ottosen et al., 2021).

LCIA analysis discussion

Both Gabi ts and openLCA LCIA results for GWP100a impacts of new bricks indicated lower impacts than the median case of EPDs, albeit by a relatively small margin. However, when compared to Boverket's case, the impact was far higher than the other two cases. This could be attributed to Boverket's conservative approach to calculating GWP values (Boverket, 2022). The assessment of environmental impacts for reused brick revealed that Gamle Mursten's EPD and Boverket's case exhibited lower impacts compared to GaBi ts and openLCA. The EoL scenarios indicated that EoL scenario 2 (crushing bricks) resulted in the highest impact, whereas EoL scenario 1 (reuse bricks) had the lowest impact for reused bricks. Notably, GaBi ts and openLCA demonstrated negative impacts for module D, which can be attributed to the corresponding virgin materials avoided.

GaBi's LCIA findings reveal that coal has the most significant impact of 3.7E+02 kgCO_2eq./t, mainly due to its high GHG emissions upon combustion (Koroneos & Dompros, 2007). The subsequent impact rankings include natural gas, biogas, and the Swedish electricity mix. Notably, the Swedish electricity mix primarily derives from hydro and nuclear power, whereas electricity sourced from wind power presents the least impact (Swedish Energy Agency, 2021). In comparison to GaBi, openLCA reports the highest GWP100a impacts from the Swedish electricity mix at 7.2E+01 kgCO_2eq./t, followed by coal, natural gas, and electricity from wind power. The higher impact of the Swedish electricity mix in openLCA could be attributed to the utilisation of outdated input flows in the used ELCD database. This highlights the importance of energy use during the production stage, as it directly affects the potential benefits of reuse and recovery.

Price comparison discussion

The cost per square meter of both products at the factory gate was observed to be similar. However, the financial feasibility of these products is not solely based on their selling price, but also their associated transportation costs. The reused bricks have a comparative advantage over new bricks due to their lower transportation costs as the facilities are located in Sweden (Brukspecialisten, 2023), which ultimately leads to a lower landing cost. Additionally, reusing bricks is an environmentally friendly option that can help reduce waste and cut down on production costs (Minunno et al., 2020). It is important to note that the financial feasibility of these products may depend on several factors beyond their transportation and production costs, such as installation costs, loading costs, and material wastage, the inclusion of which can be taken up for future study. Therefore, a more detailed and comprehensive cost-benefit analysis may be required to accurately determine the most financially feasible option.

Comparative study discussion

As for the comparative study, the environmental impact of new brick cases was found to be higher than the median of EPDs. Boverket's case was 2.5 times higher than the median case. In contrast, GaBi and openLCA cases were closer at 70.4 % and 63.5 % of the median case, respectively. On the other hand, all reused brick cases had a lower GWP impact than the median EPD value and save around 50 % which is consistent with Papadaki et al.'s value of 43 % (Papadaki et al., 2022).

The findings of an EoL study suggested that EoL 1 cases that undergo cleaning and reuse had the least impact. This indicates that, if the circular approach was more widely adopted, EoL 1 would be the optimal solution even for a new brick. However, as Galvão (2018) has observed, there is a multitude of barriers, including economic considerations and a lack of societal pressure (Araujo Galvão et al., 2018). Interestingly, EoL 2 (crushed) and EoL 3 (landfill) had similar results with EoL 2 slightly higher. While EoL 2 involves crushing the brick, which requires energy, EoL 3 involves disposing of the brick in a landfill, which may also require energy for transportation and disposal. Thus, the energy inputs and outputs of both methods may be comparable, leading to similar impacts. As reported by Minunno (2020), the results of this study indicate a consensus that the reuse of bricks can lead to additional reductions in GHG emissions (Minunno et al., 2020).

To summarise, while the use of new bricks and fossil fuels is unavoidable in construction and energy generation, there are promising alternatives that can drastically reduce their environmental harms. Reusing bricks at the EoW stage and switching to cleaner renewable energy sources pose significant benefits over conventional approaches. Reusing existing bricks avoids resource depletion, air, and water pollution, GHG emissions, and waste generation associated with producing new bricks. The manufacturing of bricks has a large environmental footprint, so reusing bricks provide tremendous impact reductions. Similarly, renewable energy has zero direct emissions, reduces reliance on finite fuels, and promotes energy security and independence (El Chaar & Lamont, 2010).

5. Conclusion

The study has achieved its aim of comparing the environmental performance of reused bricks and newly manufactured bricks used in the Swedish Construction Industry. To realise this aim, relevant data were obtained from the published type III EPDs of clay bricks in European Program Operators. Product-specific data and Boverket Klimatdatabas scenarios were used to calculate the impacts of LCA software. The parametric study was conducted in LCA software for various energy sources used in the product stage. Data obtained was analysed in Excel, Tableau and Python to identify the most favourable case.

Through the finding of this study, it can be ascertained that materials with higher reuse potential have lower environmental impacts. By using cleaner and renewable primary energy sources the total lifecycle environmental impacts of products can be reduced. In conclusion, this study highlights the need for more comprehensive and standardised approaches to EPDs to better assess the environmental performance of building materials. The environmental impact of the construction industry is a growing concern, and therefore it is important to address this issue. The findings suggest that there are ways to mitigate this impact, such as reusing bricks through reclamation and switching to renewable energy sources like wind power. It was evident that reclaiming process of used bricks also has adverse environmental impacts, but they are significantly lower than that compared to using newly manufactured bricks and fossil fuels.

Furthermore, the financial feasibility of these products may depend on several factors beyond their transportation and production costs, such as installation costs, loading costs, and material wastage. Therefore, it is important to conduct a more detailed and comprehensive cost-benefit analysis to accurately determine the most financially feasible option. This will require further research into the different factors that affect the cost of these products.

These observations have several implications for further research, not only into the reusability potential of different building materials in the sub-structure and super-structure of buildings but also into a more harmonised PCR for circular materials. Designing for durability, disassembly and urban mining approaches of circular economy can also be studied.

In response to the increasing need for sustainable building materials, it is crucial to conduct further investigation and adopt circular construction practices to reduce the brick industry's environmental impact. By reusing existing bricks and shifting to renewable energy sources, energy independence can be promoted, and reliance on finite fuels and GHG emissions can be significantly decreased. Achieving this goal will require collaboration among industry stakeholders, researchers, and policymakers to develop comprehensive and effective strategies for promoting sustainable building practices.

References

Almeida, M. I., Dias, A. C., Demertzi, M., & Arroja, L. (2015). Contribution to the development of product category rules for ceramic bricks. *Journal of Cleaner Production*, *92*, 206–215. https://doi.org/10.1016/J.JCLEPRO.2014.12.073

Araujo Galvão, G. D., De Nadae, J., Clemente, D. H., Chinen, G., & De Carvalho, M. M. (2018). Circular Economy: Overview of Barriers. *Procedia CIRP*, *73*, 79–85. https://doi.org/10.1016/J.PROCIR.2018.04.011

Bovea, M. D., Saura, Ú., Ferrero, J. L., & Giner, J. (2007). Cradle-to-gate study of red clay for use in the ceramic industry. *International Journal of Life Cycle Assessment*, *12*(6), 439–447. https://doi.org/10.1065/LCA2006.06.252

Boverket. (2020). *Utveckling av regler om klimatdeklaration av byggnader*. https://www.boverket.se/sv/om-boverket/publicerat-av-boverket/publikationer/2020/utveckling-av-regler-om-klimatdeklaration-av-byggnader/

Boverket, K. (2022). *Brick, Klimatdeklaration*. https://www.boverket.se/sv/klimatdeklaration/klimatdatabas/klimatdatabas/GetResourceByCategoryID/

Brukspecialisten. (2023). *Reused bricks – Brukspecialisten*. https://brukspecialisten.se/faq-aterbrukat-tegel/

Buchanan, A. H., & Honey, B. G. (1994). Energy and carbon dioxide implications of building construction. *Energy and Buildings*, *20*(3), 205–217. https://doi.org/10.1016/0378-7788(94)90024-8

Danish Ministry of Climate, E. and U. (2021). *Green Gas Strategy*. https://ens.dk/sites/ens.dk/files/Naturgas/groen_gasstrategi_en.pdf

David W, P., & R. Kerry, T. (1990). *Economics of Natural Resources and the Environment - David W. Pearce, R. Kerry Turner - Google Books*. Harvester Wheatsheaf. https://books.google.se/books?id=ex8vaG6m4RMC&printsec=frontcover&source=gbs_ge_summary_r&cad=0#v=onepage&q&f=false

EEA. (2015). *Closing the loop - An EU action plan for the Circular Economy COM/2015/0614 final — European Environment Agency*. https://www.eea.europa.eu/policy-documents/com-2015-0614-final

Ekvall, T., Björklund, A., Sandin, G., Jelse, K., Lagergren, J., & Rydberg, M. (2020). *Modeling recycling in life cycle assessment*. https://www.lifecyclecenter.se/wp-content/uploads/2020_05_Modeling-recyling-in-life-cycle-assessment-1.pdf

El Chaar, L., & Lamont, L. A. (2010). Nourishing green minds in the land of oil. *Renewable Energy*, *35*(3), 570–575. https://doi.org/10.1016/J.RENENE.2009.08.015

Gelowitz, M. D. C., & McArthur, J. J. (2017). Comparison of type III environmental product declarations for construction products: Material sourcing and harmonization evaluation. *Journal of Cleaner Production*, *157*, 125–133. https://doi.org/10.1016/J.JCLEPRO.2017.04.133

GreenDelta. (2022). *OpenLCA 1.11.0*.

Jane Anderson, A. B. M. & D. of C. (2020). *EPD: Where to Find - The Alliance for Sustainable Building Products*. https://asbp.org.uk/briefing-paper/epd-where-to-find

Johan Weihe et al. (2022). *A brief overview of the growing green gas production in Denmark*. https://www.bechbruun.com/en/news/2022/a-brief-overview-of-the-growing-green-gas-production-in-denmark

JRC. (2015). *European reference Life Cycle Database of the Joint Research Center Version 3.2 from October 2015*.

Jupyter. (2023). *Jupyter Lab*. https://jupyter.org/

Kinuthia, J., Marcelino, S., Oti, J., & Seco, A. (2018). Problems encountered in the life cycle assessment (LCA) of recycled materials in construction. *Lecture Notes in Civil Engineering*, *6*, 48–64. https://doi.org/10.1007/978-3-319-63709-9_5

Koomey, J. G., Martin, N. C., Brown, M., Price, L. K., & Levine, M. D. (1998). Costs of reducing carbon emissions: US building sector scenarios. *Energy Policy*, *26*(5), 433–440. https://doi.org/10.1016/S0301-4215(97)00154-7

Koroneos, C., & Dompros, A. (2007). Environmental assessment of brick production in Greece. *Building and Environment*, *42*(5), 2114–2123. https://doi.org/10.1016/J.BUILDENV.2006.03.006

Lechner, N. (2015). *Heating, Cooling, Lighting : Sustainable Design Methods for Architects* (Fourth). John Wiley & Sons, Inc.

Lourenço, P. B., & Vasconcelos, G. (2015). The design and mechanical performance of high-performance perforated fired masonry bricks. *Eco-Efficient Masonry Bricks and Blocks: Design, Properties and Durability*, 13–44. https://doi.org/10.1016/B978-1-78242-305-8.00002-4

Matplotlib. (2023). *Matplotlib 3.7*. https://matplotlib.org/

Microsoft. (2022). *Microsoft Excel Spreadsheet Software | Microsoft 365*. https://www.microsoft.com/sv-se/microsoft-365/excel

Minkov, N., Schneider, L., Lehmann, A., & Finkbeiner, M. (2015). Type III Environmental Declaration Programmes and harmonization of product category rules: status quo and practical challenges. *Journal of Cleaner Production*, *94*, 235–246. https://doi.org/10.1016/J.JCLEPRO.2015.02.012

Minunno, R., O'Grady, T., Morrison, G. M., & Gruner, R. L. (2020). Exploring environmental benefits of reuse and recycle practices: A circular economy case study of a modular building. *Resources, Conservation and Recycling*, *160*. https://doi.org/10.1016/J.RESCONREC.2020.104855

Moré, F. B., Galindro, B. M., & Soares, S. R. (2022). Assessing the completeness and comparability of environmental product declarations. *Journal of Cleaner Production*, *375*. https://doi.org/10.1016/J.JCLEPRO.2022.133999

Nath, A. J., Sileshi, G. W., Laskar, S. Y., Pathak, K., Reang, D., Nath, A., & Das, A. K. (2021). Quantifying carbon stocks and sequestration potential in agroforestry systems under divergent management scenarios relevant to India's Nationally Determined Contribution. *Journal of Cleaner Production*, *281*, 124831. https://doi.org/10.1016/J.JCLEPRO.2020.124831

Ncube, A., Matsika, R., Mangori, L., & Ulgiati, S. (2021). Moving towards resource efficiency and circular economy in the brick manufacturing sector in Zimbabwe. *Journal of Cleaner Production*, *281*. https://doi.org/10.1016/J.JCLEPRO.2020.125238

Numpy. (2023). *NumPy 1.24.2*. https://numpy.org/

Oka, T., Suzuki, M., & Konnya, T. (1993). The estimation of energy consumption and amount of pollutants due to the construction of buildings. *Energy and Buildings*, *19*(4), 303–311. https://doi.org/10.1016/0378-7788(93)90016-N

Oti, J. E., & Kinuthia, J. M. (2012). Stabilised unfired clay bricks for environmental and sustainable use. *Applied Clay Science*, *58*, 52–59. https://doi.org/10.1016/J.CLAY.2012.01.011

Ottosen, L. M., Jensen, L. B., Astrup, T. F., McAloone, T. C., Ryberg, M., Thuesen, C., Lütken, S., Christiansen, S., Damø, A. J., & Odgaard, M. H. (2021). Implementation stage for circular economy in the danish building and construction sector. *Detritus*, *16*, 26–30. https://doi.org/10.31025/2611-4135/2021.15110

Papadaki, D., Nikolaou, D. A., & Assimakopoulos, M. N. (2022). Circular Environmental Impact of Recycled Building Materials and Residential Renewable Energy. *Sustainability (Switzerland)*, *14*(7). https://doi.org/10.3390/SU14074039

Pauer, E., Wohner, B., & Tacker, M. (2020). The influence of database selection on environmental impact results. Life cycle assessment of packaging using gabi, ecoinvent 3.6, and the environmental footprint database. *Sustainability (Switzerland)*, *12*(23), 1–15. https://doi.org/10.3390/SU12239948

Prasertsan, S., & Theppaya, T. (2007). A Study Toward Energy Saving in Brick Making: Part 1-Key Parameters for Energy Saving. *International Energy Journal*.

PSF. (2023). *Python 3.11*. https://www.python.org/

Rezaei, F., Bulle, C., & Lesage, P. (2019). Integrating building information modeling and life cycle assessment in the early and detailed building design stages. *Building and Environment*, *153*, 158–167. https://doi.org/10.1016/J.BUILDENV.2019.01.034

Rizos, V., Behrens, A., van der Gaast, W., Hofman, E., Ioannou, A., Kafyeke, T., Flamos, A., Rinaldi, R., Papadelis, S., Hirschnitz-Garbers, M., & Topi, C. (2016). Implementation of Circular Economy Business Models by Small and Medium-Sized Enterprises (SMEs): Barriers and Enablers. *Sustainability 2016, Vol. 8, Page 1212*, *8*(11), 1212. https://doi.org/10.3390/SU8111212

SIS. (2021). *Sustainability of construction works - Environmental declarations - Product-specific rules SS-EN 15804:2012+A2:2019/AC:2021 - Swedish Institute for Standards, SIS*. Swedish Institute for Standards. https://www.sis.se/produkter/byggnadsmaterial-och-byggnader/byggnadsindustrin/ovriga-aspekter/ss-en-158042012a22019ac2021/

Swedish Energy Agency. (2021). *Energy in Sweden 2021 - An Overview*. https://energimyndigheten.a-w2m.se/Home.mvc?ResourceId=198022

Tableau. (2023). *Tableau Desktop | Connect, analyze, and visualize any data*. https://www.tableau.com/products/desktop

Thinkstep. (2020). *GaBi ts 9.2.168*.

Tiles & Brick Europe. (2014). *TBE PCR for Clay Construction Products Guidance document for developing an EPD 2 Tiles & Bricks Europe*. https://static1.squarespace.com/static/5629fd2ce4b065f044bf8e5a/t/563396fbe4b086a764f0afc3/1446221563987/14+10+10+TBE+PCR+guidance+document.pdf

UNEP. (2021). *2021 Global Status Report for Buildings and Construction | UNEP - UN Environment Programme*. https://www.unep.org/resources/report/2021-global-status-report-buildings-and-construction

Yu, C., Davis, C., & Dijkema, G. P. J. (2014). Understanding the Evolution of Industrial Symbiosis Research. *Journal of Industrial Ecology*, *18*(2), 280–293. https://doi.org/10.1111/JIEC.12073

Yüksek, İ., Öztaş, S. K., & Tahtalı, G. (2020). The evaluation of fired clay brick production in terms of energy efficiency: a case study in Turkey. *Energy Efficiency*, *13*(7), 1473–1483. https://doi.org/10.1007/S12053-020-09896-Y

Zabalza Bribián, I., Valero Capilla, A., & Aranda Usón, A. (2011). Life cycle assessment of building materials: Comparative analysis of energy and environmental impacts and evaluation of the eco-efficiency improvement potential. *Building and Environment*, *46*(5), 1133–1140. https://doi.org/10.1016/J.BUILDENV.2010.12.002

Zhang, H., Hara, K., Yabar, H., Yamaguchi, Y., Uwasu, M., & Morioka, T. (2009). Comparative analysis of socio-economic and environmental performances for Chinese EIPs: Case studies in Baotou, Suzhou, and Shanghai. *Sustainability Science*, *4*(2), 263–279. https://doi.org/10.1007/S11625-009-0078-0/TABLES/6

Appendix A

The EPD collected and used for analysis are presented in the table below. The EPDs in the table represent the EPDs after filtering as mentioned in the Method.

EPD Case No.	*Product*	*Owner*	*Program Operator*	*Country*	*Product Type*
	UK Clay Brick	BDA (UK)	BRE Global	UK	Brick
3	Facade System with brick shells cut from recycled bricks	Gamle Mursten ApS	EPD Norge	Norway	Used Brick Cladding System
5	Facing Brick	KNB	MRPI	Netherlands	Brick
6	Clay Pavers	KNB	MRPI	Netherlands	Clay Paver
7	Brick Masonry Block	STABILA 2 SRL	EPD Italy	Italy	Brick
8	Brick Masonry Block	STABILA 2 SRL	EPD Italy	Italy	Brick
9	Brick block for masonry and attic	Wienerberger SpA Unipersonale	EPD Italy	Italy	Brick
10	Clay Brick	Kingscourt Brick	EPD Ireland	Ireland	Brick
11	Sandfaced Clay Brick	Kingscourt Brick	EPD Ireland	Ireland	Brick
12A	Facing Bricks, Clay Pavers, and Brick Slips	Bundesverband der Deutschen Ziegelindustrie e.V.	IBU	Germany	Clay Paver
12B	Facing Bricks, Clay Pavers, and Brick Slips	Bundesverband der Deutschen Ziegelindustrie e.V.	IBU	Germany	Clay Paver
13	Grey brick based on grey burning clay Hammershøj; Biogas based	Randers Tegl A/S	EPD Denmark	Germany	Brick
14	Silka Calcium Silicate Unit	Xella Baustoffe GmbH	IBU	Germany	CalSil Unit
15	Red bricks Vindo; biogas based	Randers Tegl A/S	EPD Denmark	Germany	Brick
16	Red bricks Gandrup; Biogas based	Randers Tegl A/S	EPD Denmark	Germany	Brick
17	Red brick with iron oxide Gandrup; Biogas based	Randers Tegl A/S	EPD Denmark	Germany	Brick
18	Bricks (Unfilled)	Bundesverband der Deutschen Ziegelindustrie e.V.	IBU	Germany	Brick
19	Bricks (Filled with Insulation)	Bundesverband der Deutschen Ziegelindustrie e.V.	IBU	Germany	Brick with Insulation
20A	Sandlime Brick	Bundesverband Kalksandsteinindustrie e.V.	IBU	Germany	Brick
20B	Sandlime Brick	Bundesverband Kalksandsteinindustrie e.V.	IBU	Germany	Brick
21	Bio_bric BGV'4G	Bouyer Leroux	FDESINIES	France	Brick
22	Bgv’PV Bgv’RT1.2 Bgv’3+ Urban’bric	Bouyer Leroux	FDESINIES	France	Brick

23	Gelimatic 27 Thermo'bric G7b	Bouyer Leroux	FDESINIES	France	Brick
24	Porotherm GRF 20 Base Brick	Wienerberger POROTHERM	FDESINIES	France	Brick
25	Porotherm GRF 20 Th+ Brick	Wienerberger POROTHERM	FDESINIES	France	Brick
26	20cm Structural Brick (Laying with Thin Joints)	CTMNC	FDESINIES	France	Brick
27	Exposed Terracotta Brick	CTMNC	FDESINIES	France	Brick
28	Partition Brick of Thickness ≥80mm (excluding binder)	CTMNC	FDESINIES	France	Brick
29	Partition Brick	CTMNC	FDESINIES	France	Brick
30	Ploegsteert Facing Brick	Ploegsteert	FDESINIES	France	Brick
31	Extruded Mud Brick	Fédération Française des Tuiles et Briques	FDESINIES	France	Brick
32	Porotherm CLIMAmur 42 Brick	Wienerberger POROTHERM	FDESINIES	France	Brick
33	Eco Brick	Wienerberger	FDESINIES	France	Brick
34	Ergobric Structure Brick	Ploegsteert	FDESINIES	France	Brick
35	Maxibrique	Ploegsteert	FDESINIES	France	Brick
36	Porotherm Type A bricks	Wienerberger POROTHERM	FDESINIES	France	Brick
37	Argitech Clay Bricks	Argilus	FDESINIES	France	Brick
38	Insulated Monolith Brick	Terreal	FDESINIES	France	Brick with Insulatio n
39	Terracotta Brick 22cm x 22cm	Briqueteries du Nord	FDESINIES	France	Brick
40	Terracotta Brick 22cm x 22cm	CTMNC	FDESINIES	France	Brick
41	Bgv'costo th+	Bouyer Leroux	FDESINIES	France	Brick
42	Bgv'uno	Bouyer Leroux	FDESINIES	France	Brick
43	Hand Molded Brick	Terreal	FDESINIES	France	Brick
44	Bgv'Primo+Bgv'Costo+Bgv'Ther mo	Bouyer Leroux	FDESINIES	France	Brick
45	Eco'bric+Thermo'bric G7	Bouyer Leroux	FDESINIES	France	Brick
46	Traditional Brick	Terreal	FDESINIES	France	Brick
47	Red Clay Brick	Tileri	RTSEPD	Finland	Brick
48	Kaolinitic Clay Brick	Tileri	RTS-EPD	Finland	Brick
49	Red Clay Brick	Wienerberger Oy Ab	RTS-EPD	Finland	Brick
50A	Light Clay Brick	Wienerberger Oy Ab	RTS-EPD	Finland	Brick
50B	Light Clay Brick	Wienerberger Oy Ab	RTS-EPD	Finland	Brick
51	Rose Brick w/ Mn_3O_4	Egernsund Wienerberger A/S	Danish Technologic al Institute	Denmark	Brick
52	Rose Brick w/o Mn_3O_4	Egernsund Wienerberger A/S	Danish Technologic al Institute	Denmark	Brick
53	Yellow Brick	Egernsund Wienerberger A/S	Danish Technologic al Institute	Denmark	Brick
54	Red Brick w/ Mn_3O_4	Egernsund Wienerberger A/S	Danish Technologic al Institute	Denmark	Brick

55	Red Brick w/o Mn_3O_4	Egernsund Wienerberger A/S	Danish Technological Institute	Denmark	Brick
56A	Yellow and Sand Colored Brick	Egernsund Wienerberger A/S	Danish Technological Institute	Denmark	Brick
56B	Yellow and Sand Colored Brick	Egernsund Wienerberger A/S	Danish Technological Institute	Denmark	Brick
57A	Rose and Grey/Brown Brick	Egernsund Wienerberger A/S	Danish Technological Institute	Denmark	Brick
57B	Rose and Grey/Brown Brick	Egernsund Wienerberger A/S	Danish Technological Institute	Denmark	Brick
58A	Red Brick w/ Mn_3O_4	Egernsund Wienerberger A/S	Danish Technological Institute	Denmark	Brick
58B	Red Brick w/ Mn_3O_4	Egernsund Wienerberger A/S	Danish Technological Institute	Denmark	Brick
59A	Red Brick w/o Mn_3O_4	Egernsund Wienerberger A/S	Danish Technological Institute	Denmark	Brick
59B	Red Brick w/o Mn_3O_4	Egernsund Wienerberger A/S	Danish Technological Institute	Denmark	Brick
60	Clay Product - Kolumba or Cover	Petersen Tegl A/S	Danish Technological Institute	Denmark	Brick
61	LESS - Red or Brown Brick	Egernsund Wienerberger A/S	Danish Technological Institute	Denmark	Brick
62	LESS - Yellow Brick	Egernsund Wienerberger A/S	Danish Technological Institute	Denmark	Brick
63	LESS - Red Brick w/o Mn_3O_4	Egernsund Wienerberger A/S	Danish Technological Institute	Denmark	Brick
64	LESS - Black or Grey Brick w/o Mn_3O_4	Egernsund Wienerberger A/S	Danish Technological Institute	Denmark	Brick
65A	Black or Grey Brick w/ Mn_3O_4	Egernsund Wienerberger A/S	Danish Technological Institute	Denmark	Brick
65B	Black or Grey Brick w/ Mn_3O_4	Egernsund Wienerberger A/S	Danish Technological Institute	Denmark	Brick
66A	Rose Brick w/o Mn_3O_4	Egernsund Wienerberger A/S	Danish Technological Institute	Denmark	Brick
66B	Rose Brick w/o Mn_3O_4	Egernsund Wienerberger A/S	Danish Technological Institute	Denmark	Brick
67A	Yellow Brick	Egernsund Wienerberger A/S	Danish Technological Institute	Denmark	Brick

67B	Yellow Brick	Egernsund Wienerberger A/S	Danish Technological Institute	Denmark	Brick
68A	Red or Brown Brick	Egernsund Wienerberger A/S	Danish Technological Institute	Denmark	Brick
68B	Red or Brown Brick	Egernsund Wienerberger A/S	Danish Technological Institute	Denmark	Brick
69	GREENER - Rose Brick	Randers Tegl A/S	Danish Technological Institute	Denmark	Brick
70	GREENER - Yellow Brick	Randers Tegl A/S	Danish Technological Institute	Denmark	Brick
71	GREENER - Red Brick w/ Fe_2O_3	Randers Tegl A/S	Danish Technological Institute	Denmark	Brick
72	GREENER - Red Brick w/ Mn_3O_4	Randers Tegl A/S	Danish Technological Institute	Denmark	Brick
73	GREENER - Red Brick	Randers Tegl A/S	Danish Technological Institute	Denmark	Brick
74	Yellow-red/Rose Subdued Brick	Strøjer Tegl	Danish Technological Institute	Denmark	Brick
75	Yellow-red/Rose Brick	Strøjer Tegl	Danish Technological Institute	Denmark	Brick
76	Yellow Subdued Brick	Strøjer Tegl	Danish Technological Institute	Denmark	Brick
77	Yellow Brick	Strøjer Tegl	Danish Technological Institute	Denmark	Brick
78	Red Subdued Brick	Strøjer Tegl	Danish Technological Institute	Denmark	Brick
79	Red Brick	Strøjer Tegl	Danish Technological Institute	Denmark	Brick
80	Rose Brick	Randers Tegl A/S	Danish Technological Institute	Denmark	Brick
81	Yellow Brick	Randers Tegl A/S	Danish Technological Institute	Denmark	Brick
82	Red Brick w/ Fe_2O_3	Randers Tegl A/S	Danish Technological Institute	Denmark	Brick
83	Red Brick w/ Mn_3O_4	Randers Tegl A/S	Danish Technological Institute	Denmark	Brick
84	Red Brick	Randers Tegl A/S	Danish Technological Institute	Denmark	Brick

85	LESS - Rose Brick w/ Mn_3O_4	Egernsund Wienerberger A/S	Danish Technological Institute	Denmark	Brick
86	LESS - Rose Brick w/o Mn_3O_4	Egernsund Wienerberger A/S	Danish Technological Institute	Denmark	Brick
87	LESS - Yellow Brick	Egernsund Wienerberger A/S	Danish Technological Institute	Denmark	Brick
88	LESS - Red Brick w/ Mn_3O_4	Egernsund Wienerberger A/S	Danish Technological Institute	Denmark	Brick
89	LESS - Red Brick w/o Mn_3O_4	Egernsund Wienerberger A/S	Danish Technological Institute	Denmark	Brick
90A	Clay Tiles - Pantheon Nordic	Komproment	Danish Technological Institute	Denmark	Clay Tiles
90B	Clay Tiles - Colosseum Nordic	Komproment	Danish Technological Institute	Denmark	Clay Tiles
91	Yellow Brick	Randers Tegl A/S	Danish Technological Institute	Denmark	Brick
92	Grey Brick	Randers Tegl A/S	Danish Technological Institute	Denmark	Brick
93	Red Brick	Randers Tegl A/S	Danish Technological Institute	Denmark	Brick
94A	Red Brick	Matzen Tegl: A/S Carl Matzen Teglværk	Danish Technological Institute	Denmark	Brick
94B	Yellow Brick	Matzen Tegl: A/S Carl Matzen Teglværk	Danish Technological Institute	Denmark	Brick
95A	Red Brick	Matzen Tegl: A/S Graasten Teglværk	Danish Technological Institute	Denmark	Brick
95B	Yellow Brick	Matzen Tegl: A/S Graasten Teglværk	Danish Technological Institute	Denmark	Brick
95C	Black Brick	Matzen Tegl: A/S Graasten Teglværk	Danish Technological Institute	Denmark	Brick
96	GREENER - Rose Brick	Randers Tegl A/S	Danish Technological Institute	Denmark	Brick
97	GREENER - Yellow Brick	Randers Tegl A/S	Danish Technological Institute	Denmark	Brick
98	GREENER - Red Brick	Randers Tegl A/S	Danish Technological Institute	Denmark	Brick
99A	Red Brick	Matzen Tegl: A/S Carl Matzen Teglværk	Danish Technological Institute	Denmark	Brick

99B	Yellow Brick	Matzen Tegl: A/S Carl Matzen Teglværk	Danish Technological Institute	Denmark	Brick
100A	Red Brick	Matzen Tegl: A/S Graasten Teglværk	Danish Technological Institute	Denmark	Brick
100B	Yellow Brick	Matzen Tegl: A/S Graasten Teglværk	Danish Technological Institute	Denmark	Brick
100C	Black Brick	Matzen Tegl: A/S Graasten Teglværk	Danish Technological Institute	Denmark	Brick
101	Rose Brick	Randers Tegl A/S	Danish Technological Institute	Denmark	Brick
102	Yellow Brick	Randers Tegl A/S	Danish Technological Institute	Denmark	Brick
103	Red Brick	Randers Tegl A/S	Danish Technological Institute	Denmark	Brick
104A	Clay Brick - D-bricks	Petersen Tegl A/S	Danish Technological Institute	Denmark	Brick
104B	Clay Brick - Kolumba and Cover	Petersen Tegl A/S	Danish Technological Institute	Denmark	Clay Tiles
105	Yellow Brick	Randers Tegl A/S	Danish Technological Institute	Denmark	Double Fired Brick
106	Grey Brick	Randers Tegl A/S	Danish Technological Institute	Denmark	Double Fired Brick
107	Red Brick	Randers Tegl A/S	Danish Technological Institute	Denmark	Double Fired Brick
108	Bricks - Ecoinvent	Initiative Ziegel	Bau-EPD	Austria	Brick
109	Bricks - Gabi	Initiative Ziegel	Bau-EPD	Austria	Brick
110	Clay Roof Tiles - Ecoinvent	Initiative Ziegel	Bau-EPD	Austria	Clay Tiles
111	Clay Roof Tiles - Gabi	Initiative Ziegel	Bau-EPD	Austria	Clay Tiles
112	Hand-made Brick	Saray Tuğla	EPD Turkey	Turkey	Brick
114	TerraCotta Tile	Şahtaş Seramik ve Toprak	EPD Turkey	Turkey	Clay Tiles
115	Hollow Brick and Brick Products	HELUZ	EPD International AB	Sweden	Brick
116A	Perforated Dense Facing Bricks - White coloured	Marshalls Bricks & Masonry	EPD International AB	Sweden	Brick
116B	Perforated Dense Facing Bricks - strong coloured	Marshalls Bricks & Masonry	EPD International AB	Sweden	Brick
116C	Perforated Dense Facing Bricks - light coloured	Marshalls Bricks & Masonry	EPD International AB	Sweden	Brick

117	Ceramic Board	HISPALYT	AENOR	Spain	Clay Tiles
118	Ceramic Pavers	HISPALYT	AENOR	Spain	Clay Paver
119	Ceramic Vaults and Caissons	HISPALYT	AENOR	Spain	Brick
120	Bricks and Ceramic Pavers	HISPALYT	AENOR	Spain	Brick
121	Clay Roof Tiles	HISPALYT	AENOR	Spain	Clay Tiles
122	Clay Facing Bricks	HISPALYT	AENOR	Spain	Brick
123	Bricks and Ceramic Blocks	CERANOR S.A	AENOR	Spain	Brick
124	Ceramic Vaults and Caissons	CERANOR S.A	AENOR	Spain	Brick
125	Porotherm bricks and Porotherm system solutions	Wienerberger d.o.o	ZAG EPD	Slovenia	Brick
126A	Porotherm S bricks	Wienerberger d.o.o	ZAG EPD	Slovenia	Brick
126B	Porotherm Profi bricks	Wienerberger d.o.o	ZAG EPD	Slovenia	Brick
127	Single Fried Wall Tiles	GRES PANARIA PORTUGAL, S.A.	centroHabitat	Portugal	Clay Tiles
128	Used bricks (whole and half), machine cleaned, and hand sorted	Gamle Mursten ApS	Danish Technological Institute	Denmark	Used Brick

Appendix B

All inputs and outputs in various processes in the life cycle modelling of newly manufactured brick and reused brick are shown in the figures below.

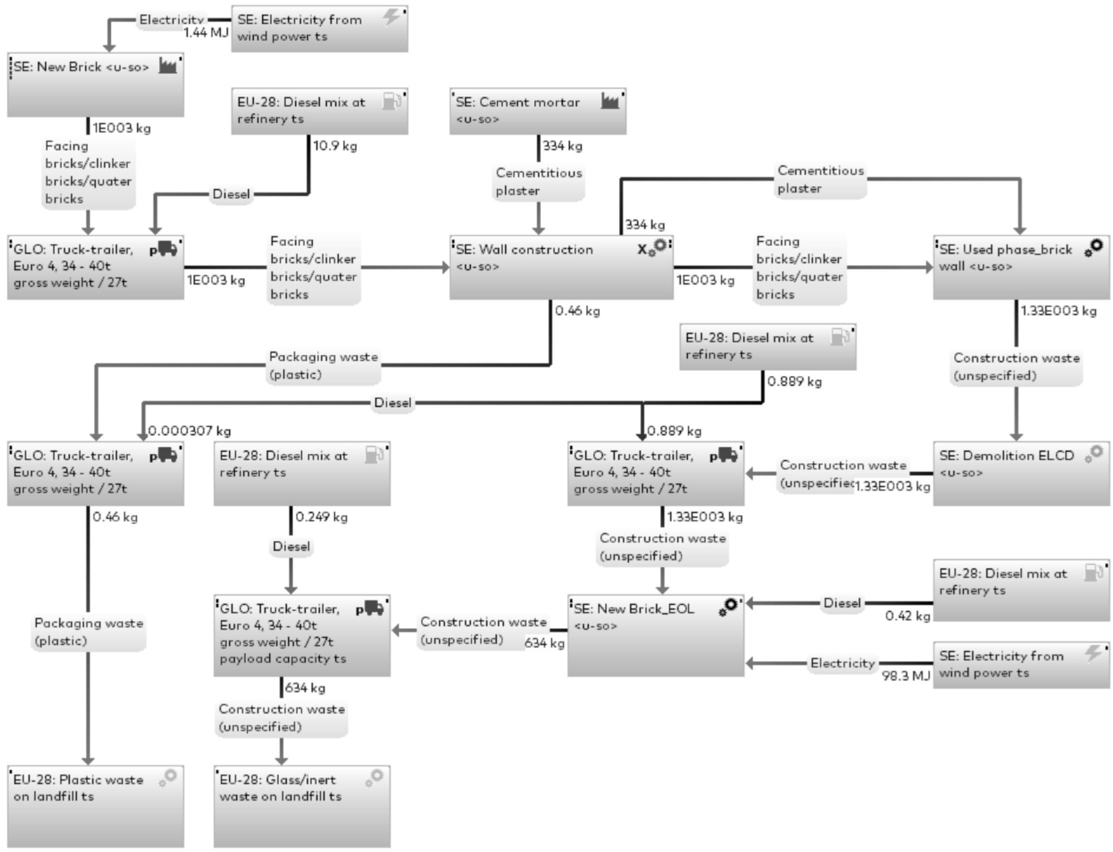

Figure: GaBi ts flow diagram showing inputs and outputs for LCIA of new brick.

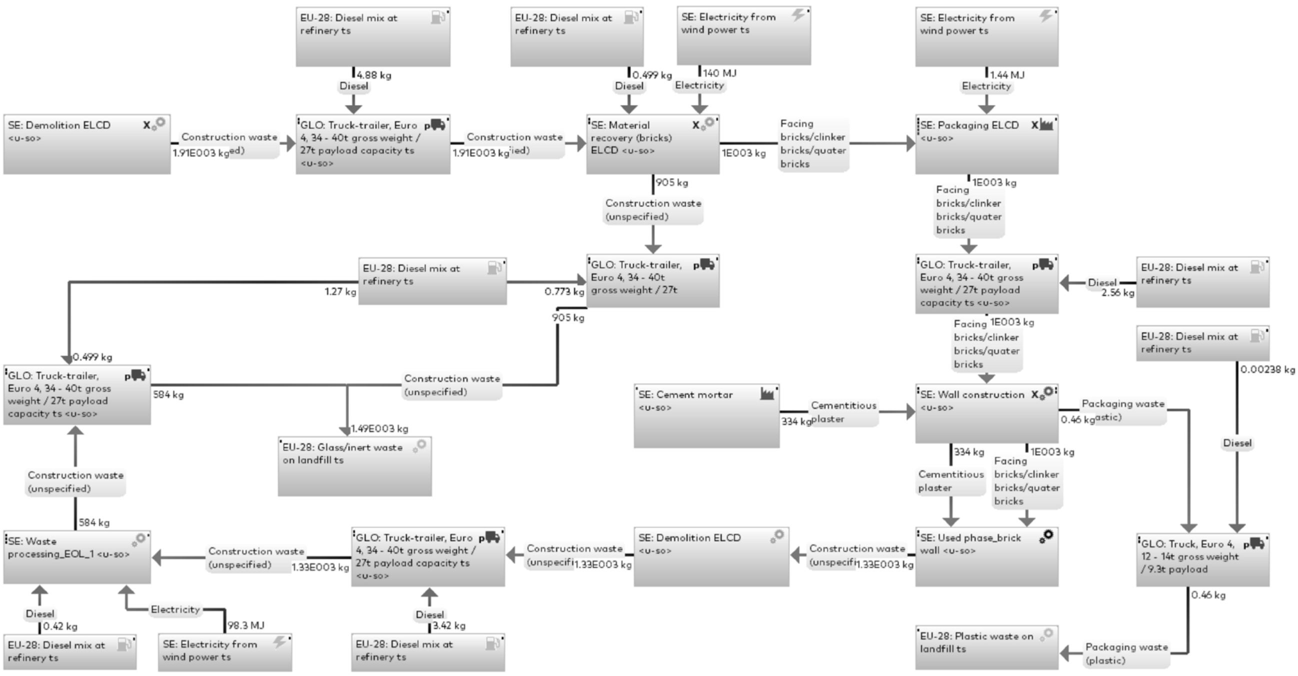

Figure: GaBi ts flow diagram showing inputs and outputs for LCIA of reused brick.

Appendix C

The impacts of Module D: Beyond the system boundary, was calculated by using the below-mentioned equation, which is adapted from EN 15804 A2 (2019) according to section 6.4.3.3. As there is only one product in the output the equation used is adapted accordingly.

$$e_{module\ D} = (M_{MR\ out} - M_{MR\ in}) \times (E_{MR\ after\ EoW\ out} - E_{VM\ sub\ out} \times (Q_{R\ out} \div Q_{Sub}))$$

$e_{module\ D}$	The net impact of loads and benefits beyond the system boundary per FU of output for module D
$M_{MR\ out}$	amount of material exiting the system that will be recovered (recycled and reused) in a subsequent system. This amount is determined at the end-of-waste point and is therefore equal to the output flow of “materials to recycling [kg]” reported for modules A4, A5, B and C;
$M_{MR\ in}$	amount of input material to the production system that has been recovered (recycled or reused) from a previous system (determined at the system boundary);
$E_{MR\ after\ EoW\ out}$	specific emissions and resources consumed per unit of analysis arising from material recovery (recycling and reusing) processes of a subsequent system after the end-of-waste state
$E_{VM\ sub\ out}$	specific emissions and resources consumed per unit of analysis arising from acquisition and pre-processing of the primary material, or average input material if primary material is not used, from the cradle to the point of functional equivalence where it would substitute secondary material that would be used in a subsequent system
$Q_{R\ out}$	quality of the outgoing recovered material (recycled and reused), i.e., quality of the recycled material at the point of substitution;
Q_{Sub}	quality of the substituted material, i.e., quality of primary material or quality of the average input material if primary material is not used;

The EoL scenarios for new brick (NB) and reused brick (RB) for GaBi and openLCA are shown tables below:

Case	RB_GaBi_EoL-1		RB_GaBi_EoL-2		RB_GaBi_EoL-3		NB_GaBi	
Output	Brick	Brick Agg	Brick	Brick Agg	Brick	Brick Agg	Brick	Brick Agg
$M_{MR\ out}$	1	0	0	1	1	1	1	0
$M_{MR\ in}$	0.25	0	0	0.3	1	1	0.3	0
$M_{MR\ out}$ - $M_{MR\ in}$	0.75	0	0	0.7	0	0	0.7	0
$E_{MR\ after\ EoW\ out}$	1.71E+01	1.71E+01	1.71E+01	1.71E+01	1.71E+01	1.71E+01	1.71E+01	1.71E+01
$E_{VM\ sub\ out}$	1.43E+02	1.36E+00	1.43E+02	1.36E+00	1.43E+02	1.36E+00	1.43E+02	1.36E+00
$Q_{R\ out}$ / Q_{Sub}	1	1	1	1	1	1	1	1

Case	RB_OpenLCA_EoL-1		RB_OpenLCA_EoL-2		RB_OpenLCA_EoL-3		NB_OpenLCA	
Output	Brick	Brick Agg	Brick	Brick Agg	Brick	Brick Agg	Brick	Brick Agg
$M_{MR\ out}$	1	0	0	1	1	1	1	0
$M_{MR\ in}$	0.25	0	0	0.3	1	1	0.3	0
$M_{MR\ out}$ - $M_{MR\ in}$	0.75	0	0	0.7	0	0	0.7	0
$E_{MR\ after\ EoW\ out}$	1.45E+01	1.45E+01	1.45E+01	1.45E+01	1.45E+01	1.45E+01	1.45E+01	1.45E+01
$E_{VM\ sub\ out}$	1.43E+02	1.36E+00	1.43E+02	1.36E+00	1.43E+02	1.36E+00	1.43E+02	1.36E+00
$Q_{R\ out}$ / Q_{Sub}	1	1	1	1	1	1	1	1

Note: The impacts of the substituted virgin materials were adopted median values of EPDs of related materials.

LUND UNIVERSITY

Divisions of Energy and Building Design, Building Physics and Building Services
Department of Building and Environmental Technology