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# External Wall Systems in Passive House Standard: Material, Thermal and Environmental LCA Analysis

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**Abstract:** The construction sector, a significant consumer of energy, possesses the potential to realize substantial environmental and economic advantages through the adoption of innovative technologies and design approaches. Notably, the Passive House standard, exemplified by energy-efficient single-family homes, emerges as a prominent solution. This study analyzes five external wall systems across multiple stages: (i) a literature review and examination of external wall techniques within the passive standard, utilizing the Passive House Database; (ii) a material and technological assessment of three wood-based and two masonry constructions; (iii) an in-depth thermal performance analysis of selected external partitions; and (iv) a Life Cycle Assessment (LCA) of the external wall systems. Our findings indicate that among the single-family homes built to the passive standard, 50.94% utilized timber constructions, while 34.21% employed masonry. Thermal analysis revealed that the masonry wall, EW-M-01, exhibited superior thermal efficiency with a heat transfer coefficient (U-value) of 0.0889 W/m$^2$K. Meanwhile, the wooden wall, EW-T-01, led its category with a U-value of 0.1000 W/m$^2$K. The LCA highlighted that the wooden wall EW-T-02 presented the lowest integrated non-renewable energy demand (PENTR) at 425.70 MJ/kg and the most favorable Global Warming Potential (GWP), with a reduction of 55.51 kg $CO_2$e. Conversely, the masonry wall EW-M-01 recorded the highest energy demand and $CO_2$e emissions, at 780.96 MJ/kg and 90.59 kg $CO_2$e, respectively. Water consumption was lowest for the EW-T-02 wooden wall (0.08 m$^3$) and highest for the EW-M-02 masonry wall (0.19 m$^3$). Conclusively, our analysis of passive house external walls demonstrates that wood-based systems offer superior performance in terms of materials, thermal efficiency, and LCA indicators, positioning them as the preferred option for sustainable passive construction.

**Keywords:** passive building design; energy efficiency; Life Cycle Assessment (LCA); green building; carbon footprint; sustainable architecture; thermal performance

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## 1. Introduction

Today's challenges in securing energy supply for the construction sector include a number of problems such as scarcity of raw materials, limited supply availability, and significant price fluctuations [1,2]. These challenges are linked to the meeting of a wide range of societal needs, including the three traditional dimensions of a sustainable energy system: environmental balance, energy security, and economic stability [3]. The problems of energy security for the construction sector are exacerbated by the increasingly visible effects of climate change, which has a significant impact on this sector [4,5]. In 2022, the construction sector will account for 34% of total global energy demand, resulting from both operational emissions from the use of building services and emissions associated with the production of building materials. The share of this sector in global energy consumption is significant, reaching about one third of the total demand [6,7]. A detailed analysis shows that emissions from the operation of buildings account for 26% of total emissions, while emissions from the production of materials such as cement, steel, and aluminium account for 7% [8]. These data underline the need to seek energy savings and to implement sustainable methods of energy production in order to reduce the negative impact of human activity on the environment [9–12].

As a major energy consumer, the building sector has the opportunity to achieve significant environmental and economic benefits through the implementation of modern technologies and design practices [13]. In particular, these changes are expected in technologies for heating and cooling buildings, which account for 40–50% of the total global final energy demand of buildings [14]. In this context, an increasing number of investors are paying attention to the realization of buildings characterized by reduced energy demand and the possibility of economic use [15–17]. An example of this thinking is the concept of passive buildings, which set new standards in sustainable design due to their exceptionally low energy consumption for heating and cooling. It is estimated that passive buildings can save 80–90% of operating energy compared to standard buildings, depending on the climate zone [18,19]. Passive houses, with their unique architecture and use of innovative technologies, provide comfortable indoor conditions in both summer and winter without the need for traditional heating or cooling systems. Often, a suitable membrane used in the wall construction is sufficient to provide durable protection to the wall structure and improve thermal insulation efficiency [20]. A key aspect of achieving such high energy efficiency is maintaining the thermal load of the building at a level not exceeding 10 $W/m^2$ [19,21]. The application of strict criteria in passive houses, such as limiting the annual heating demand to about 15 $kWh/(m^2/year)$, significantly reduces the need to use external energy sources. Achieving energy efficiency requires an integrated design approach, taking into account the site, the orientation of the building relative to the compass, the foundation methods, as well as the use of advanced insulation materials and airtightness [21–24]. In addition, the design of passive houses often incorporate renewable energy sources, such as solar panels or heat pumps. Such solutions allow not only a significant reduction in the carbon footprint, but also a reduction in the operating costs associated with heating and cooling the building. This is confirmed by a study conducted by Oddbjørn [25], according to which the use of passive internal building partitions in combination with a heat pump system can provide savings of almost 40% compared to electrically heated houses.

Energy-efficient construction, with a particular focus on passive buildings, is a key element of strategies to reduce energy consumption and greenhouse gas emissions in the construction sector [26,27]. Passive buildings can reduce cooling requirements in multistorey residential buildings by up to 36.8% due to their unique construction and applied building solutions, including external partitions [28]. The savings in energy consumption are significant, but a full environmental impact also requires consideration of information on the building materials used [29,30]. A holistic approach to analyzing such buildings, taking into account their impact on the natural environment throughout their life cycle, is possible through the application of Life Cycle Assessment (LCA) methodology [31–34]. The LCA method allows a thorough assessment of the environmental footprint of a building, covering all stages from the extraction of raw materials, production of building materials, construction, and operation to demolition and recycling [35–37]. Such a comprehensive analysis enables not only an understanding of the direct energy savings resulting from the use of the building, but also an assessment of its overall environmental impact, which is crucial for promoting sustainable development in the construction sector [38,39]. Buildings constructed in accordance with the principles of the passive construction standard can significantly contribute to the reduction of greenhouse gas emissions, as confirmed in LCA, particularly in the building use phases defined as B1 to B6. Passive houses are designed to maximize their energy efficiency, allowing for heating, cooling, and the production of domestic hot water with minimal energy consumption, often utilizing renewable sources [40,41]. This directly results in lower greenhouse gas emissions during phases B1—building use, B6—energy use, and B7—water use. LCA analyses show that passive buildings have a significantly lower energy demand compared to traditionally constructed buildings, which directly contributes to the reduction of $CO_2$e emissions. This is possible thanks to the use of advanced insulation solutions, air tightness, and the optimization of natural light and heat. Moreover, careful design and construction in accordance with the rigorous standards of passive buildings, the use of high-quality building materials, and modern technologies are crucial for increasing the durability of the building and its components, positively impacting LCA phases such as B2—maintenance, B3—repair, B4—replacement, and B5—renovation [42,43]. Thus, passive construction not only offers benefits in terms of energy efficiency and occupant comfort but also plays a significant role in strategies to reduce the construction sector's impact on climate change. By applying the principles of passive construction, it is possible to significantly lower $CO_2$e emissions over the entire life cycle of the building, making these technologies and design approaches key elements in the pursuit of sustainable development and environmentally friendly construction.

The aim of this publication is to carry out an environmental assessment of the materials used in the construction of external walls of passive single-family dwellings, considering different technologies and material configurations. The publication serves as a supplement to other research in the field of environmental LCA studies conducted for buildings constructed to passive house standards. A publication by Kylili et al. [44], which presents the LCA of a passive house in a subtropical climate zone, suggests that additional insulating materials in the building's wall systems do not significantly affect the energy embodied in the building. On the other hand, Utama et al. [45] highlight that the construction costs of external walls can account for up to 50% of a passive house's budget; also considering their lifespan, they constitute a significant element of a single-family building. Therefore, the current state of research, well indicated by Palumbo [46], shows that passive buildings should take into account not only the energy efficiency of these materials and devices but also the environmental profiles of the materials they are made from. LCA analysis will make it possible to evaluate and compare different methods of constructing external walls in terms of their environmental impact. The research focuses on identifying materials and construction solutions that provide optimal thermal insulation and minimize negative impacts on the natural environment. This publication aims to provide best practice in the design and implementation of passive buildings, which can serve as a model for future construction projects aiming to achieve high energy efficiency and low environmental impact. By analyzing various material options for external partitions, this work contributes to the development of knowledge on sustainable construction and promotes an approach that combines economic benefits with environmental protection.

## 2. Materials and Methods

In this article, the methods of implementing external walls of single-family buildings in the energy-efficient passive standard were analyzed. The research was conducted in the following stages (Figure 1).

- Stage 1. Literature analysis and technical methods of implementing external wall systems in the energy-efficient passive standard. For this purpose, the Passive House Database (https://passivehouse-database.org), managed by the Passive House Institute, Passivhaus Dienstleistung GmbH, Darmstad, Germany, IG Passivhaus Deutschland, and the iPHA (International Passive House Association) was analyzed. Based on the analysis of the database of examples of single-family buildings in the energy-efficient passive standard, it appears that in over 85% of cases, the most commonly used types of construction are wooden (50.94%) and masonry (34.21%) (Results 3.1).
- Stage 2. External partitions. In this part of the research, a material and technological analysis of external walls in realized passive homes using wooden and masonry technology was conducted. This part of the study presented five typical types of external wall partitions used in the construction of passive homes—three wooden partitions and two in masonry technology (Results 3.2).

- Stage 3. Thermal analysis of external partitions. Additionally, to obtain more accurate results, calculations of the heat transfer coefficient of walls and temperature distribution in the partition using the Finite Element Method (FEM) were conducted with THERM 7.7 software. These results are a key source of information about the thermal performance of external partitions, which is significant for designing buildings with high energy efficiency (Results 3.3).
- Stage 4. Environmental LCA studies. The LCA analysis was conducted in accordance with the EN 15978 standard [47]. The authors applied the cradle-to-gate methodology for the product phase: A1 (raw material extraction), A2 (transport to the production site), A3 (product production). The research analyzed emissions generated by the building materials used in the external wall partitions as specified in Tables 2 and 3. Table 4 contains a summary of the building materials used in the partitions. Meanwhile, information about the emissivity of materials was obtained from the public database ÖKOBAUDAT [48], which is in accordance with the EN 15804+A2 standard [49] (Results 3.4).

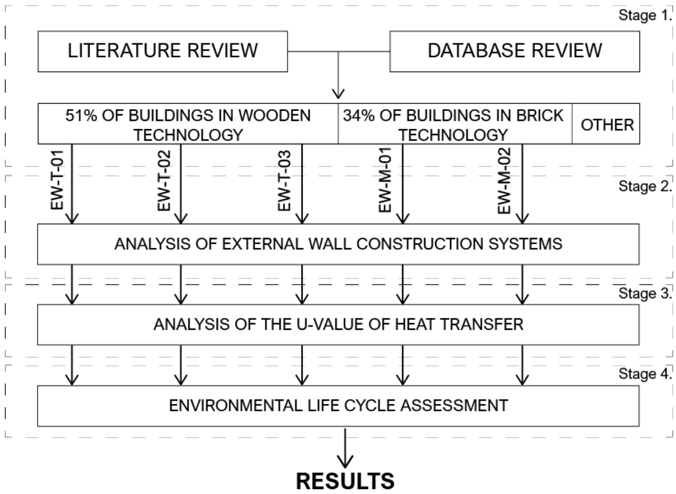



**Figure 1.** Methodology scheme. The abbreviations EW-T-01, EW-T-02, EW-T-03, EW-M-01, EW-M-02 refer to the case studies described in Section 3.2.

To conduct environmental studies in construction, the Life Cycle Assessment (LCA) analysis method is becoming increasingly common practice. The basis for the studies are the ISO 14040 [50] and ISO 14044 [51] standards, which are key standards concerning the assessment in studies of the carbon footprint of buildings and building materials [52]. The LCA analysis method is a comprehensive research method that considers all stages of a building's life cycle: from raw material acquisition, through production, construction, and use, to demolition and recycling [53,54]. The LCA method is widely used in studies of buildings' carbon footprint due to its holistic approach and consideration of many aspects [55–57].

In this publication, the LCA method was applied to conduct environmental impact studies of analyzed building partitions: (i) three in wooden construction and (ii) two in masonry construction. Following the LCA methodology guidelines, the studies consist of the following stages:

- Defining the goal and scope. In accordance with the guidelines of the ISO 14040 standard [50], this part of the study should define:
    - The intended application. The main goal of the LCA study is to compare five external wall building partitions used in single-family residential construction in the passive (energy-efficient) building system. The authors applied the cradle-to-gate methodology for the product phase: A1 (raw material extraction), A2 (transport to the production site), A3 (product production). The scope of the

study includes three external wall partitions in wooden construction (named: EW-T-01, EW-T-02, and EW-T-03) and two partitions in masonry construction (named: EW-M-01 and EW-M-02). A detailed listing of building materials and information about their thickness are described in Tables 1 and 2. The sample for the study is a rectangular prism being a fragment of the analyzed external wall, according to Figure 2.

    ○ Reasons for carrying out the study. The main reason for conducting the study is the need to understand and assess the environmental impact of different external wall constructions used in single-family residential construction. The LCA method allows for a holistic approach to analysis, covering various aspects of the carbon footprint of buildings and building materials, in accordance with ISO 14040 [50] and ISO 14044 [51] standards.
    ○ The audience. The research is directed to a wide audience in the construction industry, including designers, engineers, contractors, and institutions regulating building standards. Additionally, the results of the study may interest researchers and ecologists focused on sustainable development and minimizing the impact of construction on the environment.
    ○ Whether the results will be used in a comparative assertion released publicly. The results of the study will be made publicly available and may be used for further research. The conducted studies are of a public nature, with no private client for the research.

- Inventory Analysis. At this stage, a detailed analysis of the building materials used in the construction was conducted. For this purpose, the publicly available ÖKOBAUDAT database [48], in accordance with the EN 15804+A2 standard [49], was referenced. The ÖKOBAUDAT platform, provided by the Federal Ministry for Housing, Urban Development, and Construction, serves as a standard database designed to facilitate ecological assessments of buildings. This comprehensive platform is integral in promoting sustainable construction practices, as it offers valuable data on the environmental impact of various building materials and components. It provides access to a wealth of information, including Life Cycle Assessment (LCA) results and other relevant environmental data. Table 4 contains a compilation of the building materials used in the partitions. It should be noted that this method refers exclusively to the embodied impact (embodied carbon footprint).
- Impact Assessment. The environmental impact assessment of the building's external wall samples includes a compilation of three environmental issues: (1) Total consumption of non-renewable primary energy (PENRT), expressed in MJ; (2) Emission of Global Warming Potential (GWP), expressed in kg $CO_2$e; and (3) Net water consumption (FW), expressed in $m^3$.
- Data Interpretation. Identifying significant issues for the presented LCA studies of building partitions in passive (energy-efficient) buildings concerns three partitions in wooden construction and two in masonry construction. The configuration of the layer system in the walls and selected building materials were prepared by the study's authors. In comparative studies of research results with other authors' findings, it should be considered whether it is possible to compare these partitions regarding the layout and thickness of layers or the material used. Next, the source of data on the emissivity of building materials should be compared. The ÖKOBAUDAT database focuses on the reliability of information provided by manufacturers of building materials used in Germany, but also in parts of Europe (including Poland). Compiling study results with publications based on data from other countries or parts of the world can be significantly different due to factors including the production process, the source of the raw material, and transportation.

**Table 1.** Emissions produced by construction materials, data source [48].

| Material | Unit | Density (kg/m$^3$) | Embodied Energy (MJ) PENRT A1-3 | Carbon Data (kg $CO_2$/unit) | Water m$^3$ |
|---|---|---|---|---|---|
| Construction timber | kg/m$^3$ | 492.92 | 1142.7 | −671.84 | 0.1558 |
| Internal gypsum plaster | kg/m$^3$ | 1000.00 | 87.27 | 119.40 | 0.2412 |
| Steel galvanized | kg | 7850.00 | 25.86 | 2.78 | 0.0031 |
| Gypsum plaster board | kg/m$^2$ | 10.00 | 35.23 | 1.67 | 0.0094 |
| SwisskronO OSB | kg/m$^3$ | 614.50 | 3950.00 | −890.00 | 0.7980 |
| Stone wool insulation | kg/m$^3$ | 155.00 | 1836.00 | 196.60 | 0.4590 |
| PE foil dimpled | kg/m$^2$ | 1.20 | 114.70 | 4.12 | 0.0161 |
| Cross-laminated timber CLT | kg/m$^3$ | 489.41 | 1851.91 | −659.8 | 0.3983 |
| Silicone resin plaster | kg | | 13.79 | 0.6921 | 0.0219 |
| Wood fiber insulation (wood-based panels) STEICO | kg/m$^3$ | 60.00 | 1065.50 | −28.27 | 0.22465 |
| Plywood of hardwood veneer | kg/m$^3$ | 796.24 | 6212.55 | −914.83 | 1.4789 |
| Expanded polystyrene (EPS), gray | kg/m$^3$ | 15.00 | 1439.73 | 58.61 | 0.2822 |
| Lime cement mortar | kg/m$^3$ | 1800.00 | 823.93 | 187.7 | 0.4509 |
| Sand-lime brick | kg/m$^3$ | 2000.00 | 2219.37 | 305.53 | 0.04119 |
| AAC block | kg/m$^3$ | - | 1225.00 | 171.49 | 0.41376 |

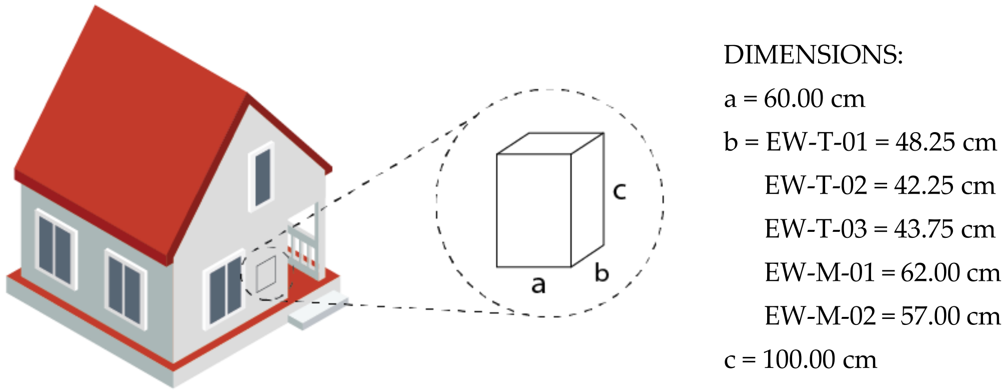



**Figure 2.** Diagram of the research sample.

## 3. Results

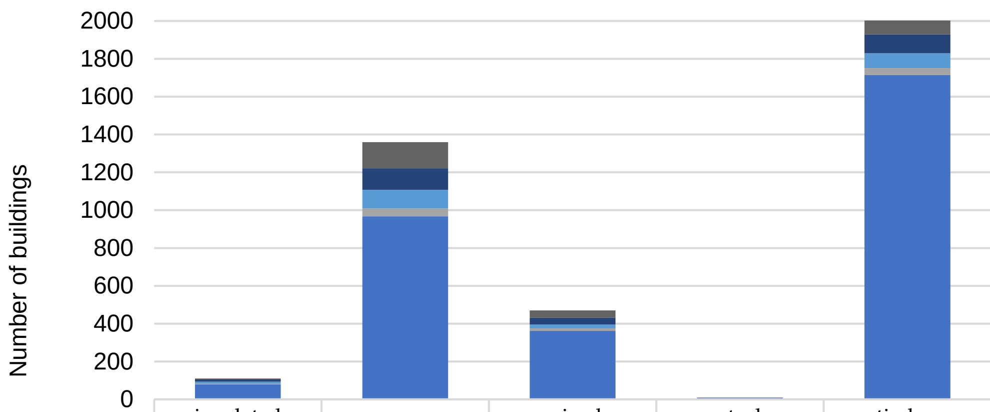
### *3.1. Database of Analyzed Passive Energy-Efficient Buildings*

Within the scope of this research, an analysis of single-family homes built in energy-efficient passive construction technology was conducted. Data concerning these buildings were verified and sourced from the publicly accessible "Passive House Database" [58]. The database contains information about buildings varying in many aspects—from function, through sizes, to location. For the purposes of this research, buildings were selected for analysis that meet specific criteria: (i) the primary function of the building is residential, (ii) the maximum size is 2 stories, additionally, it may contain a usable attic, and (iii) availability of complete data about their structural layout. The publication utilized a division into construction types of buildings, which was previously established by the authors of the "Passive House Database" [58]. Five types of construction, representative for single-family residential buildings in the passive standard, were distinguished:

- Insulated Concrete Forms, ICF: This construction type uses synthetic material forms that serve as permanent insulation for concrete walls. ICFs provide excellent thermal and acoustic insulation and are exceptionally resistant to external factors, such as extreme weather conditions or pests.
- Masonry Construction: These constructions rely on the use of bricks, concrete blocks, or other masonry materials. They are valued for their durability, fire resistance, and thermal mass, which helps maintain a stable temperature inside the building.

- Mixed Construction: This category includes buildings that combine different techniques and construction materials, e.g., steel and concrete, wood and brick, etc. Such a configuration allows for the optimization of the building's thermal and structural properties, as well as greater flexibility in design.
- Steel Construction: Steel is used in both the framework and the external elements of the structure. It is characterized by high strength, long lifespan, and is often used in modern construction. Steel constructions can be efficiently insulated and are usually faster to construct than traditional techniques.
- Timber Construction: Wood is a renewable resource that, if properly managed, can be an ecological choice for construction. Timber constructions offer good insulation properties, are lightweight, and can be relatively quickly assembled. Wood also adds a natural aesthetic element to the building design.

In Figure 3, the construction types of buildings along with their division into building types are presented. Each of the building types possesses unique features and advantages in the context of energy efficiency and application in passive construction. The discussion of these aspects constitutes an essential part of this research work, allowing for a deeper understanding and assessment of the efficiency of various construction methods in the context of achieving high energy savings.




| | insulated concrete forms | masonry construction | mixed construction | steel construction | timber construction |
|---|---|---|---|---|---|
| terraced house | 5 | 138 | 38 | 1 | 95 |
| semi-detached house | 12 | 113 | 36 | 0 | 100 |
| two-family house | 9 | 99 | 21 | 0 | 78 |
| single-family house + separate apartment | 4 | 42 | 13 | 0 | 37 |
| detached single family house | 80 | 967 | 362 | 9 | 1714 |

**Figure 3.** Division of construction types in energy-efficient residential construction in the passive standard, based on the database [35].

Based on the data presented in Figure 3, a clear trend can be observed among investors in choosing wood-based technology for the realization of single-family residential construction. Detached single-family houses show a decisive quantitative advantage in the database, accounting for 3132 of the 3973 buildings in the entire analyzed database. Detached single-family houses constitute 78.83% of all buildings in the database. Next are terraced houses, with a quantity of 277 units, accounting for 6.97% of the entire database. A similar percentage, also 6.57%, is represented by semi-detached houses, with a number of 261 units. These data indicate a lesser, but stable, popularity of this form of residential buildings among investors and developers. In the context of the above data, it can be concluded that the real estate market for single-family residential buildings in the passive standard is dominated by detached single-family houses in wooden technology, constituting 43.14% of the database. For buildings of the semi-detached house (2.84%) and terraced house (3.47%)

types, the greatest interest is in the realization of homes in masonry technology, but it is worth noting that the quantity is only slightly greater than in wooden technology.

Further quantitative analysis presented in Figure 4 showed that the most commonly used types of construction are wooden constructions, constituting 50.94% of all analyzed cases, and masonry with a share of 34.21%.

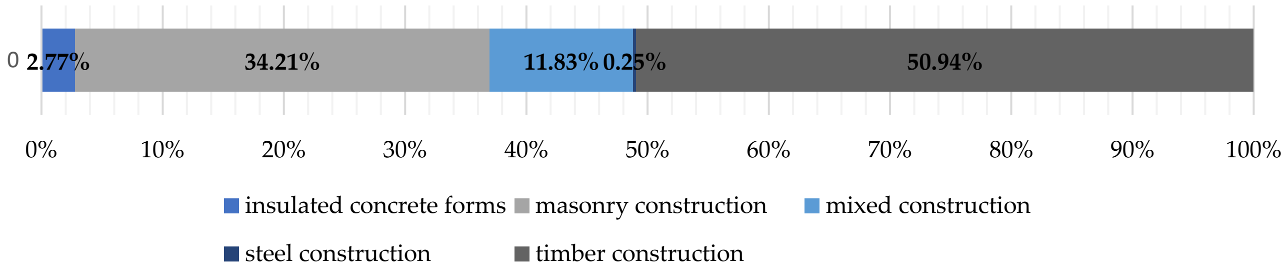



**Figure 4.** Percentage share of types of construction systems in the analyzed database of single-family residential buildings realized in the passive construction standard.

### *3.2. External Partitions*

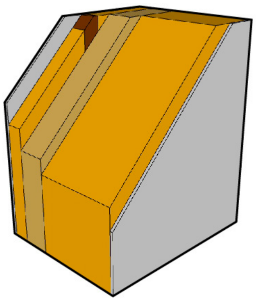
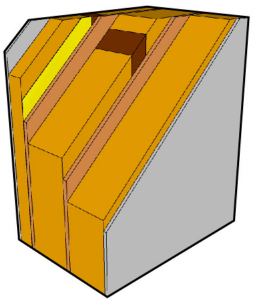
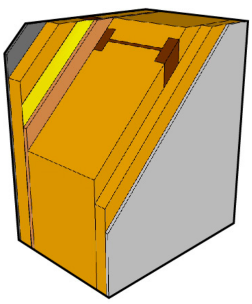
In the next stage of research, a material analysis of the external walls of single-family homes in the passive standard, for two construction systems—wooden and masonry, will be conducted. It is planned to develop and examine three typical types of external wall partitions for wooden construction and two for masonry construction. This approach was chosen to provide a focused and detailed examination of these prevalent construction methods within the context of passive house standards. By focusing on these five walls, the study aims to cover a broad spectrum of real-world applications and provide insights that are directly applicable to the majority of passive house constructions. A key element of the analysis will be the evaluation of the heat transfer coefficient and the distribution of temperatures inside the partition for the assumed external temperature for each of the selected partitions, which will allow for determining their energy efficiency and impact on the overall energy balance of the building. The goal is to identify construction solutions that provide optimal thermal insulation and minimize heat loss, which is crucial for passive construction standards.

#### 3.2.1. External Walls in Wooden Construction

External walls in wooden construction are a popular choice for energy-efficient buildings, as well as those in the passive standard. Computational and in situ studies confirm a number of positive properties of such a solution [59–61]. The most frequently discussed property is thermal resistance, which allows for reducing the thickness of the external wall partition while maintaining high resistance to heat [62–64]. At the same time, the frame construction of external walls enables the elimination of thermal bridges, thanks to the use of additional insulating partitions. The elimination of thermal bridges is one of the basic design principles of passive buildings [65,66] which enables energy savings. This dependency was confirmed in the study by H. Zou [67], who examined the walls of a passive house in a cold region.

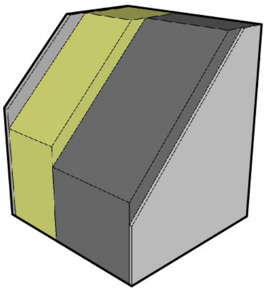
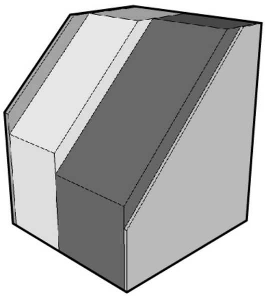
In this part of the publication, the authors have conducted a detailed analysis of the construction solutions applied in the buildings discussed in Section 3.1. Utilizing their expertise and a thorough case study of buildings documented in the Passive House Database, the research team prepared detailed wall sections for buildings meeting passive construction standards. These sections, precisely described and classified in Tables 2 and 3, contain comprehensive information on materials, insulation techniques, and construction methods that are crucial for achieving high energy efficiency and minimizing energy demand in passive buildings. The work emphasizes the importance of accurate design and precise execution of construction details, which are key to ensuring the continuity of thermal insulation and eliminating thermal bridges, essential for meeting the rigorous criteria of the passive building standard. The presentation of these sections in Tables 2 and 3 constitutes a significant contribution to the subject literature, providing practical guidance for designers and engineers aiming to achieve the highest energy efficiency in construction projects.

**Table 2.** Cross-sections of external walls in wooden construction.

| Lp. | 3D View | Description of Layers | d (mm) | λ * (W/mK) |
|---|---|---|---|---|
| EW-T-01 |  | Plasterboard | 12.5 | 0.250 |
| | | Thermal insulation/<br>wooden battens 60 × 60 mm | 60 | 0.039<br>0.180 |
| | | Vapor barrier membrane (airtight layer) | - | 0.200 |
| | | CLT wall (5 layers) | 100 | 0.240 |
| | | Wood fiber insulation | 300 | 0.037 |
| | | Mineral plaster | 10 | 0.900 |
| EW-T-02 |  | Plasterboard | 12.5 | 0.250 |
| | | Thermal insulation/<br>wooden battens 60 × 60 mm | 60 | 0.039<br>0.180 |
| | | Vapor barrier membrane (airtight layer) | - | 0.200 |
| | | OSB/3 | 15 | 0.130 |
| | | Thermal insulation/<br>Wooden structure 160 × 60 mm | 160 | 0.037<br>0.180 |
| | | OSB/3 | 15 | 0.130 |
| | | Thermal insulation—facade wool | 150 | 0.037 |
| | | Mineral plaster | 10 | 0.900 |
| EW-T-03 |  | Plasterboard | 12.5 | 0.250 |
| | | Thermal insulation/<br>wooden battens 60 × 60 mm | 60 | 0.039<br>0.180 |
| | | Vapor barrier membrane (airtight layer) | - | 0.200 |
| | | OSB/3 | 15 | 0.130 |
| | | STEICO wall beams<br>(plywood bottom and top flange of<br>I-beam—0.24 W/mK; MDF web—0.18 W/mK) | 300 | - |
| | | STEICO protect board | 40 | 0.048 |
| | | Mineral plaster | 10 | 0.900 |

* The values of thermal conductivity coefficients come from the standard [68] or declaration of product performance values.

**Table 3.** Cross-sections of external walls in masonry construction.

| Lp. | 3D View | Description of Layers | d (mm) | λ * (W/mK) |
|---|---|---|---|---|
| EW-M-01 |  | Gypsum plaster (airtight layer) | 20 | 0.900 |
| | | Masonry wall, sand-lime block | 240 | 0.550 |
| | | Graphite polystyrene | 350 | 0.033 |
| | | Mineral plaster | 10 | 0.900 |
| EW-M-02 |  | Gypsum plaster (airtight layer) | 20 | 0.900 |
| | | Masonry wall, aerated concrete | 240 | 0.170 |
| | | Graphite polystyrene | 300 | 0.033 |
| | | Mineral plaster | 10 | 0.900 |

* The values of thermal conductivity coefficients come from the standard [68] or declaration of product performance values.

Based on the information provided in Table 2, it can be concluded that proper design of the external wall in terms of continuous thermal insulation is a key aspect of passive building construction standards. This is due to their high thermal resistance and the ability to eliminate thermal bridges, which is key to reducing energy demand for heating buildings. It is also important to focus on thermal insulation to eliminate potential thermal bridges [69,70]. The use of additional insulating partitions in the construction of external walls allows for the elimination of thermal bridges, which is in accordance with the basic principles of designing passive buildings. The elimination of thermal bridges contributes to significant energy savings, as confirmed by research. Elimination of thermal bridges significantly reduces the annual energy demand for heating spaces by 38–42% and reduces the energy demand for cooling by 8–26% [71]. The presented cross-sections of external walls represent innovative and ecological construction technologies; in particular, the use of CLT boards or hard wooden insulation boards, to ensure high energy efficiency and thermal comfort in buildings [72,73]. Wooden constructions, due to their insulating properties and the possibility of using ecological insulation materials, represent a promising solution in the context of sustainable construction. They promote not only energy savings but also the use of renewable natural resources. It should also be noted that the exact efficiency of wall sections depends on the climatic context in which a given building will be constructed [24].

When calculating the heat transfer coefficient, it is important to note that it is a thermally non-homogeneous partition due to the different arrangement of materials in the cross-section through the insulation and wooden posts. Analytically, the value of the heat transfer coefficient according to the EN ISO 6946 standard [74] can be approximately calculated by the so-called Finite Element Method (FEM) or more accurate calculations which can be performed using the FEM.

### 3.2.2. External Walls in Masonry Construction

In masonry constructions, where brick and concrete blocks are the dominant materials, a significant challenge is achieving high thermal insulation without leading to an excessive increase in wall thickness. The production process of traditional building materials, such as cement, concrete, and bricks, is characterized by high energy consumption, which translates into significant carbon dioxide emissions [75,76]. In particular, cement production is a significant source of greenhouse gases, meaning that the building materials themselves can contribute significantly to the total $CO_2$e emissions associated with the construction of a house [77,78]. The use of bricks with insulation filling or lightweight aerated concrete blocks not only improves thermal insulation but also maintains the necessary structural properties of the wall without the need to increase its thickness [79,80]. This approach not only favors better energy efficiency but also reduces the use of high-carbon emission materials.

Ensuring the continuity of thermal insulation and the elimination of thermal bridges becomes a key challenge in designing energy-efficient external wall cross-sections in masonry construction. It is crucial to apply detailed design solutions and construction techniques that prevent heat penetration through uninsulated parts of the structure. Moreover, high-quality execution and ensuring the tightness of connections are of paramount importance, directly affecting the building's energy parameters and its long-term performance [81–83]. In this context, the development and application of new, ecological building materials, which are both energy-efficient and have a lesser impact on the environment, become essential. Research into innovative materials with reduced $CO_2$e emissions, such as low-carbon concretes or ecological types of bricks, opens up new possibilities for the future development of the construction sector. Such materials can also fit into a circular economy by incorporating various types of industrial waste into their composition. Research on such materials was conducted by Wiśniewski et al. [84]

Based on the information provided in Table 3, it can be concluded that external walls in masonry construction achieve the required thermal insulation through the use of a massive masonry wall and a layer of thermal insulation. The use of bricks with insulation filling or lightweight aerated concrete blocks allows for improved thermal insulation. In both examples of walls EW-M-01 and EW-M-02, a dual-layer wall system was used with a wall thickness of 24 cm and thermal insulation of 30 to 35 cm. However, it is important to remember that the production process of building materials, such as cement, concrete, and bricks, is characterized by high energy consumption and $CO_2$e emissions, highlighting the need for ecological solutions. The quality of masonry walls is influenced by the execution method and the tightness of connections, as well as ensuring thermal continuity, which enables the elimination of thermal bridges [85].

### *3.3. Heat Transfer Coefficient Analysis for Selected External Wall Systems*

The methodology of linear simulations for calculating the heat transfer coefficient in THERM 7.7 software is based on the use of the Finite Element Method (FEM) for the analysis of heat conduction in building elements. The software was developed and made available by Lawrence Berkeley National Laboratory (LBNL) in accordance with ISO 15099:2003 [86], ISO 10077 [87], PN-EN ISO 10456:2009 [68], PN-EN ISO 6946:2017-10 [88], and PN-EN ISO 10211:2017-09 [89]. This program is particularly useful in modeling complex geometries, such as thermal bridges, windows, or various types of partitions. This method requires dividing the cross-section into a grid consisting of non-overlapping elements. This process is automatically performed by THERM using the Finite Quadtree method. After defining the geometry of the cross-section, material properties, and boundary conditions, THERM creates a grid of the section, conducts heat transfer analysis, estimates errors, if necessary, refines the grid and returns a convergent solution. Such simulations are crucial in the design of energy-efficient buildings, allowing for the identification and minimization of thermal bridges, thereby significantly improving the thermal insulation of buildings. The aim of this element of the analysis is to assess the heat transfer coefficient for each of the selected partitions, which will determine their energy efficiency and impact on the overall energy balance of the building. Calculations of the heat transfer coefficient and temperature distributions inside partitions were conducted for the winter season, assuming an indoor temperature of +20 °C and an external temperature of −18 °C, corresponding to the average calculated external temperature of European countries located in Zone 4 according to the report Towards nearly zero-energy Buildings [90], i.e., countries such as the Netherlands, Germany, Belgium, Denmark, Ireland, the United Kingdom, France, Czech Republic, Poland, which are countries with a temperate continental climate/humid continental climate without a dry season and with warm summer.

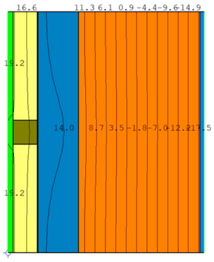
For all analyzed partitions in wooden and masonry construction, the heat transfer coefficient value is less than 0.15 $W/m^2K$. The U-values of partitions in wooden construction are slightly higher than those in masonry construction due to their specific structure, as they are thermally non-homogeneous partitions, and the total U-value is the result of individual wall sections. For this reason, the U-value calculations were conducted using the FEM. The non-homogeneity of these partitions is also evidenced by the presented temperature distributions (compare Tables 4 and 5). Plotted isotherms confirm that all analyzed partitions are correctly designed, and interlayer condensation of water vapor will not occur, although it should be noted that a detailed thermal-humidity analysis should be conducted individually for each climatic zone in a given country, as, for example, in Poland there are five climatic zones where the largest area of the country belongs to Zone III, for which the calculated external temperature in the winter period is −20 °C, while for Zone V, this temperature is −24 °C. At the same time, summers are moderately hot. As a result, indoor temperatures in buildings can vary significantly depending on the season. Well-designed and constructed external walls of a building should lower heating costs in winter and cooling costs in summer. With the appropriate construction, they should increase thermal comfort in the building, i.e., cool the rooms on hot days and protect the rooms from cooling down in winter. Theoretical approaches to this problem are discussed, for example, in [91]. In the context of the above, it is worth noting that in the case of partitions in passive buildings, thermal stability of the partition, which is determined by so-called thermal mass, also plays an important role. Buildings constructed with wooden frame technology, due to their lightweight construction, have a low capacity for heat storage. Such houses heat up quickly, but at the same time, they lose accumulated heat quickly. A low heat storage capacity may seem like a disadvantage, but if properly utilized, it can become an advantage and have a positive impact on the thermal comfort of the occupants.

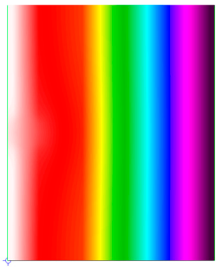
Buildings in masonry technology are characterized by a large heat accumulation (load-bearing elements). Such buildings take longer to heat up, but they also lose accumulated heat more slowly. However, heating the rooms of a masonry house to a set temperature takes much more time than achieving the same temperature in a house of wooden construction. This is because, in a masonry house, in addition to the air inside the rooms, the walls (load-bearing element made of heavy material) must also be heated. This may make it difficult to control the temperature in the rooms and adjust it to the individual needs of the occupants. This means that in masonry buildings, thermal energy accumulated in excess is inefficiently used. In a building constructed with wooden frame technology, only the air inside the rooms is heated, not the walls, which means that raising or lowering the temperature occurs almost instantly and is not associated with high fuel costs. Thanks to this sensitivity of frame constructions to changes, air conditioners of lower power can be used in the home, which will simultaneously need less energy to cool the air inside the rooms than would be the case in a masonry construction building.

The accuracy of the heat transfer coefficient analysis of partitions is undoubtedly influenced by reliable data regarding the thermal conductivity of materials that make up a given partition. Values should be based on precise laboratory measurements or appropriately verified from reliable sources, such as technical standards or manufacturers' catalogs. Additionally, these values should be continuously updated, as technologies and materials can evolve, which may affect their thermal properties. The issue of the impacts of various factors, such as sample size, drying temperature, or measuring instruments on the accuracy of thermal conductivity measurement is analyzed in the study [92].

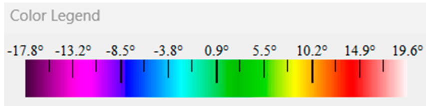
**Table 4.** Heat transfer coefficient analysis for walls in wooden construction.

Name of partition: EW-T-01

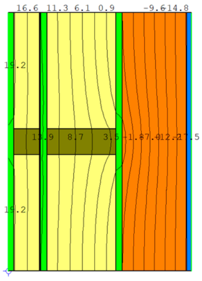


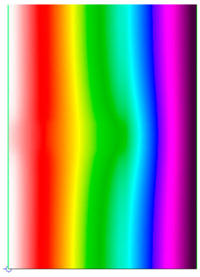


| U-factor (W/m$^2$K) | Delta T °C | Length mm |
|---|---|---|
| 0.1000 | 38.0 | 600 |

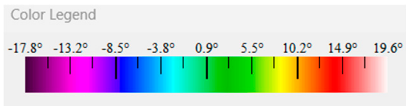



Name of partition: EW-T-02

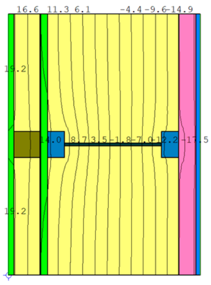


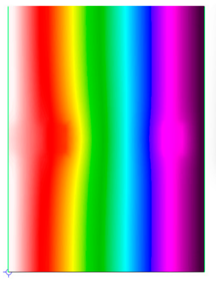


| U-factor (W/m$^2$K) | Delta T °C | Length mm |
|---|---|---|
| 0.1118 | 38.0 | 600 |




Name of partition: EW-T-03





| U-factor (W/m$^2$K) | Delta T °C | Length mm |
|---|---|---|
| 0.1048 | 38.0 | 600 |

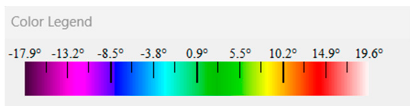
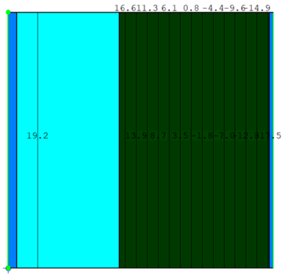
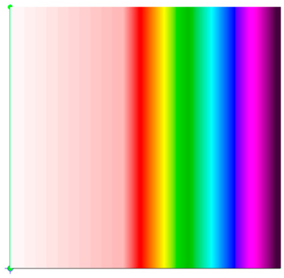
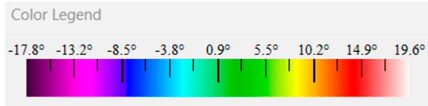
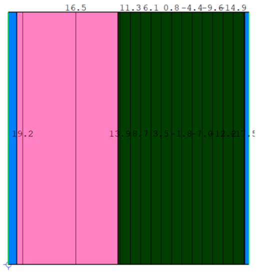
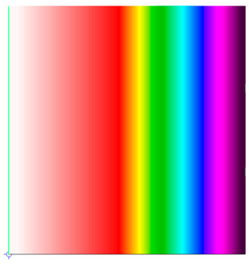
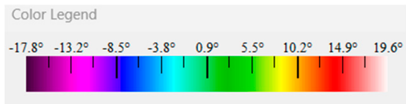


**Table 5.** Heat transfer coefficient analysis for walls in masonry construction.

| Name of partition: EW-M-01 | | | |
|---|---|---|---|
|  | | |  |
| U-factor ($W/m^2K$) | Delta T °C | Length mm |  |
| 0.0889 | 38.0 | 600 | |
| Name of partition: EW-M-02 | | | |
|  | | |  |
| U-factor ($W/m^2K$) | Delta T °C | Length mm |  |
| 0.0934 | 38.0 | 600 | |

### *3.4. Environmental Life Cycle Assessment Studies for Selected External Wall Systems*

#### 3.4.1. Embodied Energy

Embodied energy, the energy invested in the production of a building material, is a key factor in sustainable construction and its environmental impact. To accurately assess the energy expenditures for a specific material, it is essential to trace the entire flow of energy, from raw material extraction to final application [93]. This embodied energy was divided by Venkatarama Reddy and Jagadish [94] into three main areas: (1) energy used for the production of basic building materials, (2) energy needed for the transport of these materials, and (3) energy required for the assembly of various materials to erect a building.

Such activities require significant energy consumption, often from non-renewable sources, posing a threat to the biosphere. Identifying embodied energy is inseparably linked to $CO_2$e emissions. As a result, the use of building materials that intensively consume energy worsens the state of the natural environment. However, it is important to note that some data provided by manufacturers of building materials may be unreliable, which constitutes a significant drawback of these analyses. This unreliability raises concerns about the accuracy of embodied energy calculations and subsequent environmental assessments. This work focuses on production stages A1–A3 for research purposes.

In Figure 5, within the conducted LCA analysis using the cradle-to-gate method for five different wall constructions, significant differences in embodied energy were identified. Wooden walls, marked as EW-T-01, EW-T-02, and EW-T-03, showed a lower content of accumulated energy than their masonry counterparts, marked as EW-M-01 and EW-M-02. In particular, the EW-T-02 construction had the lowest level of embodied energy, amounting to 425.70 MJ/kg, suggesting exceptional energy efficiency among the studied wooden walls. Close to this result is the wall EW-T-01 with a value of 478.66 MJ/kg, which also indicates a favorable energy profile. Meanwhile, the wall EW-T-03, with embodied energy at the level of 602.02 MJ/kg, indicates a significant increase in energy consumption compared to the two previous wooden walls. Between the lowest (EW-T-01) and highest (EW-T-03) result, there is a difference of 141.56 MJ/kg, which constitutes 23.5% of the value of the wall EW-T-03. Masonry constructions presented higher values of embodied energy. The EW-M-01 wall achieved the highest result in the analysis, with a value of 780.96 MJ/kg, implying the least energy efficiency among all considered options. The EW-M-02 wall, with embodied energy equal to 580.07 MJ/kg, although performing better than EW-M-01, still remains less energy-efficient compared to wooden walls.

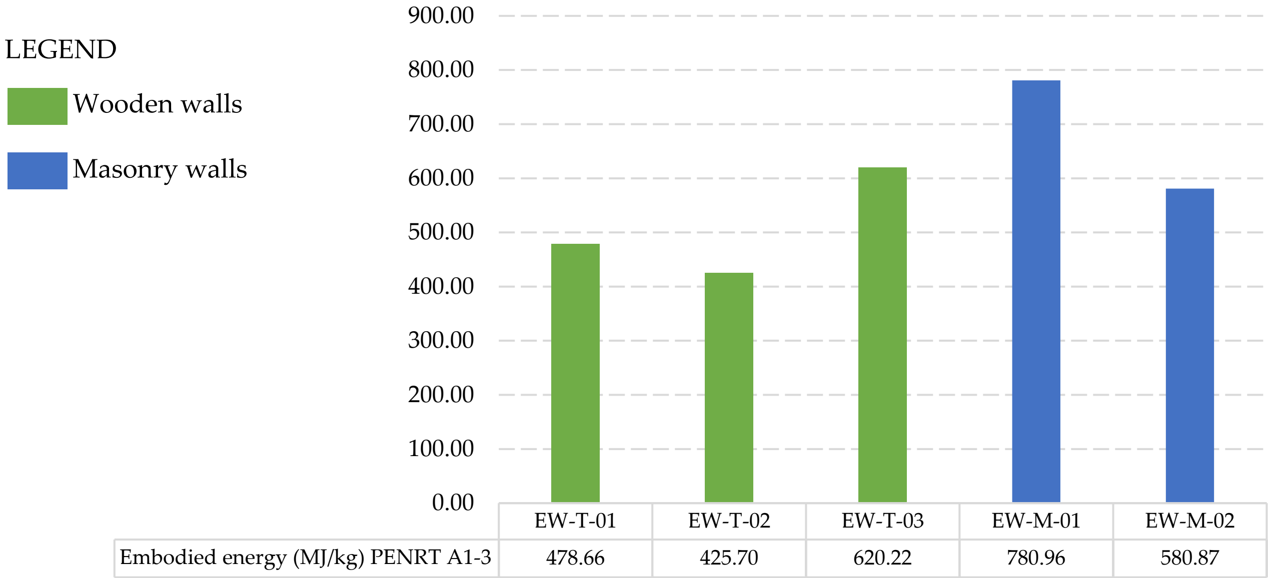



**Figure 5.** Comparison of PENRT [MJ] at production stages A1–A3.

The results indicate that the choice of building materials has a significant impact on the total energy consumption necessary for material production. Wooden constructions, presenting lower values of embodied energy, can be considered more sustainable from an energy perspective. Nonetheless, it should be emphasized that embodied energy is only one of many indicators for assessing sustainable development.

### 3.4.2. Global Warming Potential

GWP (Global Warming Potential) expressed in units of [kg $CO_2$e] refers to the process of assessing the impact that various greenhouse gases have on the greenhouse effect, using carbon dioxide as a reference point [95]. GWP is a measure of how much heat a greenhouse gas traps in the atmosphere, converting it into a mass equivalent of $CO_2$ and considering a specific time frame, most commonly 100 years [96]. This allows for the comparison of the impact of different greenhouse gases on Earth's warming on a common scale.

In Figure 6, the $CO_2$e emission results for five different types of walls in the context of their LCA stages A1–A3, which cover raw material acquisition, transport, and the production process, are presented. The $CO_2$e emission data were expressed in kilograms per unit of wall construction. The analysis of the chart reveals clear differences in the $CO_2$e emission profile between wooden and masonry constructions. Wooden constructions (EW-T-01, EW-T-02, EW-T-03) showed negative $CO_2$e emissions, which is interpreted as a result of carbon sequestration by the wooden material. The EW-T-01 construction achieved a value of −55.51 kg $CO_2$e, which is the highest level of sequestration among the studied walls. Wall EW-T-02 also showed significant sequestration, with a result of −26.44 kg $CO_2$e, and wall EW-T-03 reached a value of −21.18 kg $CO_2$e. In contrast, masonry walls (EW-M-01 and EW-M-02) present high values of $CO_2$e emissions. The EW-M-01 wall showed the highest emission, reaching 90.59 kg $CO_2$e, highlighting the significant energy consumption and associated emissions during its production. The EW-M-02 wall also showed high emission, though lower than EW-M-01, amounting to 69.53 kg $CO_2$e. The results emphasize the significant impact of the choice of building materials on the carbon footprint. Negative $CO_2$e emission values for wooden walls indicate their potential role as carbon reservoirs, which is extremely important in the context of reducing the negative impact of the construction sector on the environment and climate change. Meanwhile, high positive $CO_2$e emission values for masonry walls underscore the necessity of seeking more sustainable production methods or using alternative materials with a lower carbon footprint. Nonetheless, a comprehensive environmental impact assessment requires consideration of the entire product life cycle, not just stages A1–A3, to more accurately determine the environmental impact of a building material. Particularly for wood-based building materials, if not reused or recycled in stage D, it results in the release of accumulated $CO_2$ in stages C1–C4.

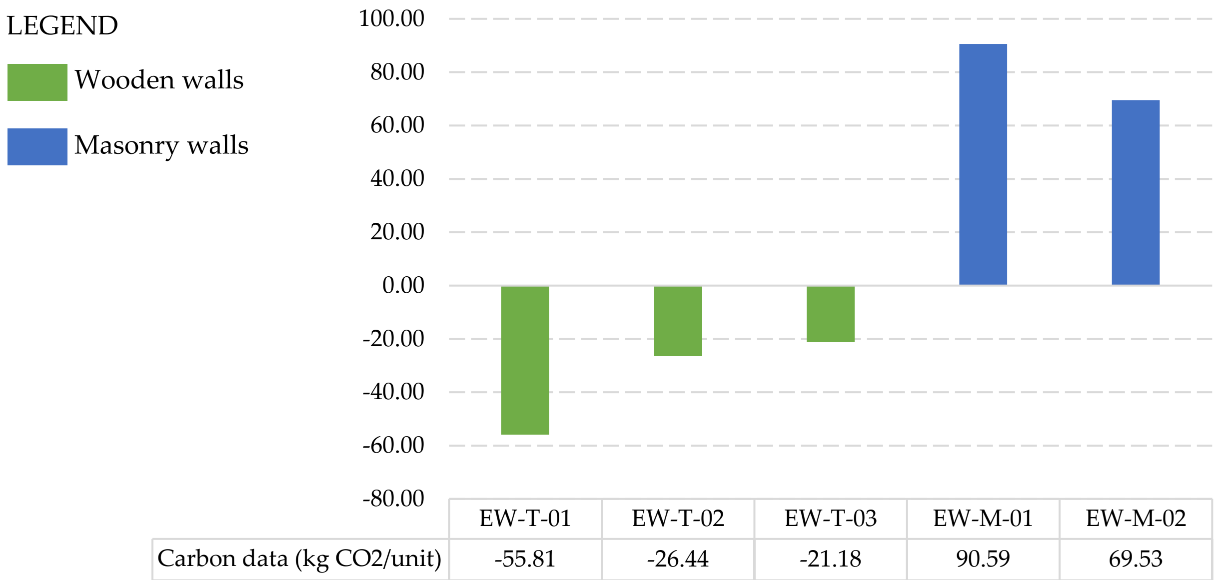



**Figure 6.** Comparison of GWP [kg $CO_2$e] at production stages A1–A3.

### 3.4.3. Water Footprint

Comparing the Water Footprint (FW) at the production stages A1–A3 of the Product Life Cycle (LCA) is crucial for understanding the impact that production processes have on water resources [97]. Stages A1–A3 include raw material acquisition, production, and transport of building materials, which have a significant impact on the use of freshwater and can generate potential effects on humans, ecosystems, and water resources. The use of freshwater in the production process of building materials such as cement, steel, or wood is critical. The production of these materials requires intensive water consumption, both in direct processes and indirect ones, such as cooling, mixing raw materials, or processing. Water scarcity, water functionality, its ecological value, and the renewability rate are factors that should be considered when assessing the production impact on water resources [98,99].

In Figure 7, the results of water consumption analysis per cubic meter ($m^3/m^3$) for five different types of walls within the A1–A3 stages of the LCA analysis are presented. Wooden walls show lower water consumption values, which may suggest a more sustainable approach in the context of water resource management. The lowest water consumption level was shown by the wall EW-T-02 and amounts to 0.08 $m^3$, which is a relatively low value, suggesting efficiency in water resource management for this type of construction. A similar result was obtained by the wall EW-T-01 with 0.09 $m^3$, while for the wall EW-T-03, an increase in consumption to 0.12 $m^3$ is observed, which is a higher value than for the other two wooden constructions. For walls in masonry construction, the results are higher, with the wall EW-M-01 consuming 0.15 $m^3$, while the wall EW-M-02 consumes 0.19 $m^3$.

The higher water consumption may be associated with the production process of masonry structural elements, which is typically more intensive in terms of water consumption than the production of wooden elements. In summary, these results show a variation in water consumption between wooden and masonry constructions, with an emphasis on greater use of water resources in the case of masonry materials. The low water consumption value for wooden constructions may indicate their potential in sustainable construction where water resource management is becoming increasingly important.

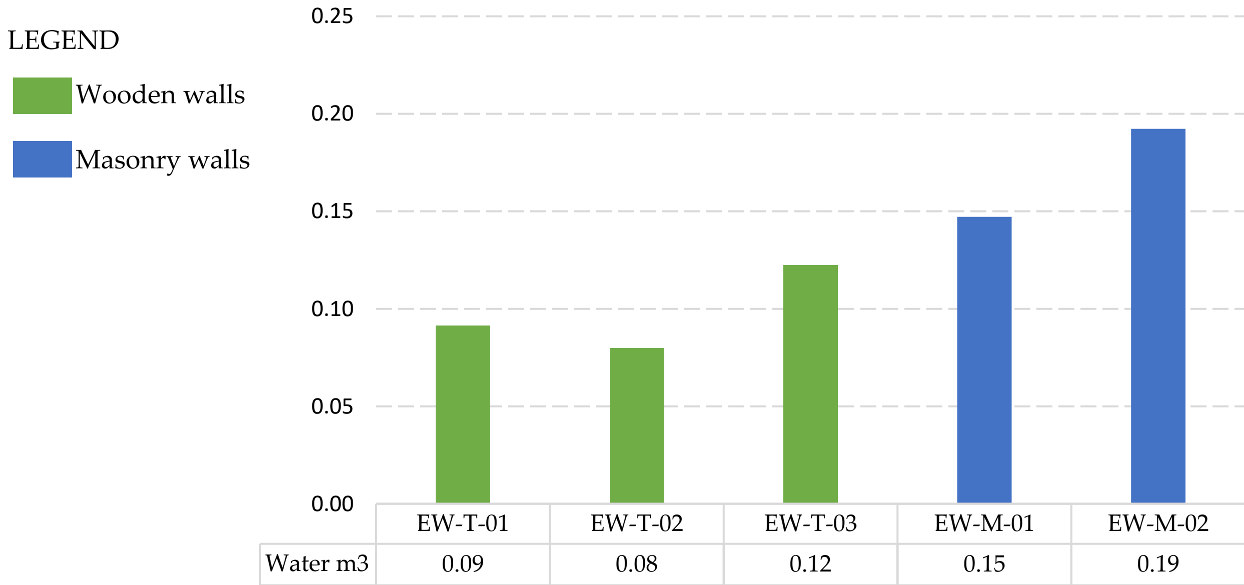



**Figure 7.** Comparison of FW [$m^3$] at production stages A1–A3.

## 4. Discussion and Conclusions

The analysis of construction types of single-family residential buildings in the passive standard, based on data from the "Passive House Database", reveals significant trends and preferences in construction technologies. The results indicate a dominance of wooden constructions, which account for over half of all analyzed cases (50.94%), highlighting a growing interest in ecological and renewable materials in construction. Masonry constructions, despite their traditional role, make up 34.21% of the analyzed buildings, indicating lesser use in the context of passive construction. These results are confirmed by the publication of Kuzman et al. [100], in which the authors suggest that wooden construction is the most suitable option for passive houses, based on comfort, psychological aspects, and functionality. This choice is also confirmed for technical reasons, where [61] conducted a thermal evaluation of selected wooden house constructions and demonstrated that they meet the strictest thermal requirements, highlighting their potential in the field of low-energy and passive construction.

This study sheds light on key aspects of material and construction technique choices in the realization of energy-efficient and passive buildings, focusing on external partitions. External walls in wooden construction, thanks to their high thermal resistance and ability to eliminate thermal bridges, represent a promising solution for passive buildings. Their use allows for significant reductions in energy demand for heating, as confirmed in studies and in situ practice. These conclusions are supported by H. Ge et al. [101], who indicate that thermal bridges in the external partitions of buildings significantly increase annual heating and cooling loads, and their impact on energy characteristics is underestimated using traditional methods. The possibility of using additional insulating partitions and eliminating thermal bridges, in accordance with the basic principles of passive building design, contributes to significant energy savings.

On the other hand, external walls in masonry construction present a traditional approach, which can also meet the requirements of passive construction, though it is associated with challenges. Ensuring high thermal insulation with limited wall thickness requires the use of materials with better insulating properties, such as bricks with insulation filling or aerated concrete blocks. However, the high energy consumption of producing traditional building materials and associated carbon dioxide emissions pose significant challenges for sustainable construction. The development of ecological building materials and construction techniques that reduce $CO_2$e emissions is crucial for the future of the sector. According to the publication by Sathre and O'Connor [102], replacing non-renewable building materials, such as concrete or steel, with wood can lead to a significant reduction in greenhouse gas emissions. The authors emphasize that wood, as a renewable material, has significant potential for carbon storage, contributing to the reduction of the building's total $CO_2$e emissions, provided that forests are managed sustainably and wood residues are used responsibly. Similar conclusions were also presented by Werner and Richter [103], who in their study highlighted that wood as a construction material generally has a favorable $CO_2$e emission profile. Biogenic carbon, playing a crucial role in the emission balance of construction, is a significant element in the context of wooden walls in buildings [104]. The use of wood in building walls allows for the "sequestration" of biogenic carbon within the structure for a long period, instead of releasing it into the atmosphere. Thus, buildings with wooden walls can contribute to the reduction of overall carbon dioxide emissions, while also serving as an example of utilizing a renewable resource [105].

The analysis of the heat transfer coefficient (U-factor) for selected external wall systems in wooden and masonry construction provides significant information regarding the energy efficiency of these solutions. The presented data show that walls in masonry construction (EW-M-01 and EW-M-02) exhibit a lower heat transfer coefficient compared to walls in wooden construction (EW-T-01, EW-T-02, EW-T-03), suggesting better thermal insulation of masonry systems. These results may be surprising, given the common perception of wood as a material with the best insulating properties. Modern masonry construction systems offer significant advantages, as highlighted by Hendry et al. [106], pointing out their improvements. This is confirmed by Brameshuber et al. [107], indicating that innovative ideas in masonry construction have led to improved thermal insulation, increased efficiency, and reduced labor costs.

Environmental studies conducted using the Life Cycle Assessment (LCA) method for selected external wall systems indicate the complexity and multidimensionality of assessing the impact of construction on the environment. The analysis of energy consumption and $CO_2$e emissions shows that wooden constructions have a lower accumulated energy content and are characterized by negative $CO_2$e emission values, resulting from carbon sequestration by the wooden material. This suggests that the use of wood in construction can contribute to the reduction of the overall carbon footprint of buildings, which is crucial in the context of global efforts to limit climate change. In contrast, masonry constructions show higher accumulated energy values and positive $CO_2$e emission values, emphasizing the need for further research on sustainable production methods and the use of masonry materials. Water consumption in the material production process was also analyzed. Wooden constructions may be more sustainable in terms of water resource management, which is an important aspect in the context of limited freshwater resources worldwide. The LCA analysis reveals the complexity of assessing the environmental impact of construction and points out significant differences between wooden and masonry constructions in terms of energy consumption, $CO_2$e emissions, and water usage. This highlights the importance of choosing materials and construction technologies in the context of striving for sustainable development. These results suggest that wooden constructions may offer a more favorable environmental profile, which should be considered in the design and construction process of sustainable buildings. However, it is important to remember that LCA is just one element of assessing sustainable construction, and a comprehensive environmental impact assessment requires considering a broader context, including durability, insulation properties, and the possibility of material reuse.

**Author Contributions:** Conceptualization, Ł.M.; methodology, Ł.M.; software, M.P. and O.S.; validation, K.J.; formal analysis, O.S. and K.J.; data curation, M.P.; writing—original draft preparation, Ł.M., M.P., O.S. and K.J.; writing—review and editing, Ł.M., M.P., O.S. and K.J. All authors have read and agreed to the published version of the manuscript.

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