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Systematic Review

Historical Building Energy Retrofit Focusing on the Whole Life Cycle Assessment—A Systematic Literature Review

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Abstract

Climate change is becoming one of humanity's major concerns. Remarkable steps are being implemented to reduce global emissions in all economic sectors, including the built environment. Historical buildings use a considerable amount of energy and produce emissions; therefore, retrofitting these buildings will enhance the global path towards zero-emissions targets. This paper applies a systematic literature review methodology to identify the research around energy efficiency retrofit in historical buildings, then analyzes this data to find out the common scopes of these studies. After that, the study focuses on the research that covered the life cycle assessment. Lastly, the paper identifies where the research in this field stands, what is accomplished, and what needs to be done. The study used two databases, ScienceDirect and the Web of Science. The output of this study that evaluated 362 publications showed that research in historical building energy efficiency has increased significantly in the last ten years. A few studies cover the topic of whole life cycle assessments and mainly focus on specific processes: energy/emissions, or specific suggested interventions. The suggested future plans for research in this area are to consider the whole life energy and emissions in retrofitted historical buildings.

Keywords: historical buildings; retrofit; energy efficiency; life cycle assessment

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1. Introduction

In the last 50 years, global warming has reached a peak. Between 1970 and 2019, it rose by 0.8–1.3 °C, and this is a direct result of human activities [1]. The CO_2 concentration in the Earth's atmosphere reached the highest level in history. And this is highly associated with extreme weather events, such as heatwaves, floods, wildfires, heavy rains, and droughts [1]. Unless significant steps are taken towards reducing emissions, future warming will be more severe. Considering that some climate change impacts will need many years to be reversible, undoubtedly, cutting carbon emissions could reduce or at least stabilize global warming [1].

Globally, buildings during construction and operation use about 40% of the total energy produced and emit about 36% of the total global emissions [2]. Existing buildings, including historical ones, are responsible for about 50% of the total energy consumption in developed countries. Therefore, implementing energy-efficiency and sustainable standards in these buildings is essential [3]. Historical buildings are any building that has cultural significance; therefore, preserving these buildings has cultural, economic, and social benefits [4]. Historic buildings are an illustration of humanity's history, with a great aesthetic value presented in their unique architectural criteria [5], as well as the communal value of these buildings as a representative of people's memories and identities [5]. Historical buildings are associated

with low energy performance compared to new builds; therefore, these buildings should be considered in any plans to improve their energy performance [3,6]. Moreover, retrofitting historical buildings goes beyond preserving the past; it is also a valuable resource for the future by many means, such as enhancing these buildings' aesthetic perception [7]. Improving energy efficiency in these buildings is essential for many reasons, such as reducing the buildings' emissions, improving indoor air quality, and enhancing the building users' comfort [8].

Recently, there has been growing attention on energy efficiency in historical buildings. This has happened for many reasons, such as the global efforts to reduce energy consumption and carbon emissions, the concerns that historical buildings will be left behind the energy-efficiency standards, and the current need to improve these buildings' comfort standards [9]. A systematic literature review of the sustainable refurbishment of historical buildings showed the following: there is a growing number of publications on the sustainable refurbishment of historical buildings, with the majority of research covering European content [10]. A considerable number of these studies selected a case study, suggested some improvement, and then measured the impact of these interventions [10]. Specifically in recent years, historical buildings' energy-efficiency refurbishment has received more attention from many research bodies. In the EU, many projects have started to examine and evaluate different methods and materials that enhance historical building energy efficiency. Some of these projects are Energy Efficiency for EU Historic Districts' Sustainability (EFFESUS), Efficient ENergy for EU Cultural Heritage (3ENCULT), and Typology Approach for Building Stock Energy Assessment (TABULA). EFFESUS is a research project that investigated the energy efficiency of European historic urban districts and developed technologies and systems for their improvement [11]. The project suggested a decision-making process to enhance historical building refurbishment in line with new software. Moreover, the project examined the application of four innovative technologies and different materials [11]. Those materials and techniques were applied to seven case studies in different countries, such as the UK, Sweden, and Germany [11]. The 3ENCULT project worked on bridging the gap between historical buildings' preservation and climate mitigation [12]. 3ENCULT demonstrated the feasibility of a reduction in energy demands, depending on the case and the heritage value [12]. Some materials and techniques were used in this project to refurbish historical buildings, and those materials and techniques were applied to eight case studies in different countries, such as Spain, Italy, and Germany [12]. After applying the interventions, the energy reduction is counted or simulated [12]. All of those projects demonstrated the valuable impacts of energy-efficient refurbishment in reducing energy consumption and emissions [12]. TABULA is a project that works to improve energy-efficiency measures in EU countries depending on the house's typology [13]. This project used different refurbishment strategies for each of the suggested typologies to improve energy efficiency [13].

Retrofitting historical buildings, focusing on the whole process of emissions, is essential to achieve the zero-emission plans [14]. In the last few decades, a considerable number of publications covered energy efficiency in historical buildings, but the majority of these publications focused on improving the operational energy/emissions performance of the building, with a few studies considering embodied energy/emissions [15]. The whole life cycle assessment (WLCA) is a tool used to measure products' or services' environmental impacts. The tool measures each stage of the product's life environmental impact, from raw material extraction, production, transport, use, and end of life, and then accumulates the total environmental impact [16]. Using WLCA in the construction sector can provide a comprehensive view of the environmental impact of the construction process and enhance decision-making to deliver sustainable buildings [16]. In the construction industry, the focus is on operational energy and operational emissions, while the impact of the embodied energy and embodied carbon is ignored or not identified in most cases [17]. Considering achieving

the target of reducing the whole-life emissions in historical buildings, more studies are needed in the area of the whole life cycle assessment in historical building retrofits [18]. Therefore, this study uses a systematic literature review to identify the main scope of the research on historic building energy retrofits and then focuses on the research that considers the whole life emissions from the retrofit. The aims are firstly, performing a comprehensive evaluation and integrating the available research in the area, secondly, identifying the knowledge in the field, and thirdly, recognizing the research gap or the knowledge that needs to be accomplished.

2. Materials and Methods

This research aims to implement a systematic literature review on the energy efficiency retrofit in historical buildings, focusing on the research that considers the whole life cycle of energy/emissions.

The research objectives are to

- Use a systematic literature review process to identify the research in the area of energy efficiency retrofits in historical buildings.
- An analysis of the research in the area of energy efficiency retrofits in historical buildings to find out the common areas and scope of these studies.
- Evaluate the studies that covered the whole life cycle assessment (WLCA) in historical building retrofits.
- Identify the research gap and the future directions for retrofitting historical buildings.

Implementing a literature review is an important research methodology that supports shaping the future of research depending on analyzing the previous studies [19]. To find out the research accomplished in the area of historical building retrofits, the systematic literature review (SLR) method was selected, for the reason that SLR is a process of collecting literature, synthesizing it, and then critiquing it to clarify what we know and what we need to know [20,21]. In other words, identify the knowledge we accomplish and the gap/s that we need to cover [20,21]. Moreover, SLR provides considerable coverage of the knowledge in the research area and helps in formulating the theoretical frame of the research [21].

There are specific steps to perform the SLR as shown in Figure 1:



Figure 1. SLR steps.

For this research, the SLR steps are as follows:

- Selecting the database: for this research, the selected databases are ScienceDirect and the Web of Science. Both databases have a remarkable number of publications in scientific research, and most of these publications have open access. ScienceDirect gives access to more than 18 million full-text articles, and 1.4 million articles are open-access [22]. Similarly, the Web of Science has 85.9 million records going back to 1900, and 17.2 million are open-access records [23]. The advantage of these platforms, when searching using keywords is that it gives every publication that has the search words in the title or the publication's abstract.
- Select the search terms: To find publications for this research, the search terms are energy—refurbishment—historical—building, as well as other terms energy—retrofit—historical—building. Retrofit and refurbishment terms are used extensively in describing the upgrading of historical buildings, but there are some differences between the two terms. Retrofit means upgrading and replacing the features of the building to improve its performance, while refurbishment means restoring and modifying the building's existing features to improve

its condition [24,25]. Of note, the selection of the search term should consider the research problem and can help in gathering all related literature to the research topic [20].

- Decide on the inclusion and exclusion criteria: Selecting the inclusion and exclusion criteria helps define the search boundary and narrow down the data to be more relevant to the research problem [20]. For this research, the inclusion and exclusion criteria are publications using the English language (according to the researcher's capabilities); open access publications (due to the complication of accessing unopen publications); publications only looking at the energy refurbishment/retrofit (as much research is focusing on the refurbishment of general historical buildings); and also, those focusing on only historical buildings (as all energy efficient building research in new build construction is not relevant to the research area).
- Start the initial search by adding the search terms to the database. When using the terms energy—refurbishment—historical—building, based on the ScienceDirect database, the result was 3864 publications, and 140 articles for the Web of Science database. While for the other terms energy—retrofit—historical—building, come with 5705 results for ScienceDirect and 425 documents for the Web of Science database.
- Applying the two inclusion and exclusion criteria, the language and open access, the result is narrowed to 755 publications for ScienceDirect and 140 articles for the Web of Science database for energy—refurbishment—historical—building. For the terms energy—retrofit—historical—building, the share narrowed to 1080 results for ScienceDirect and 420 for the Web of Science database.
- The next step is performing an initial review of the data by reviewing the title as recommended by D. Pati and L. N. Lorusso [26], but to improve the search output for all publications for which the title is not totally relevant to the research problem, the researcher read the abstract, to decide whether the publication is relevant or not. In this stage, this study excluded any research that covers some parts of the research field, such as papers that cover the topic of historical buildings only or retrofit only. The research included studies that focus on the historical building energy retrofit.

  Then, if the abstract is irrelevant, the publication was excluded from the study pool. The SLR process is described using the PRISMA flow chart as shown in Figure 2.

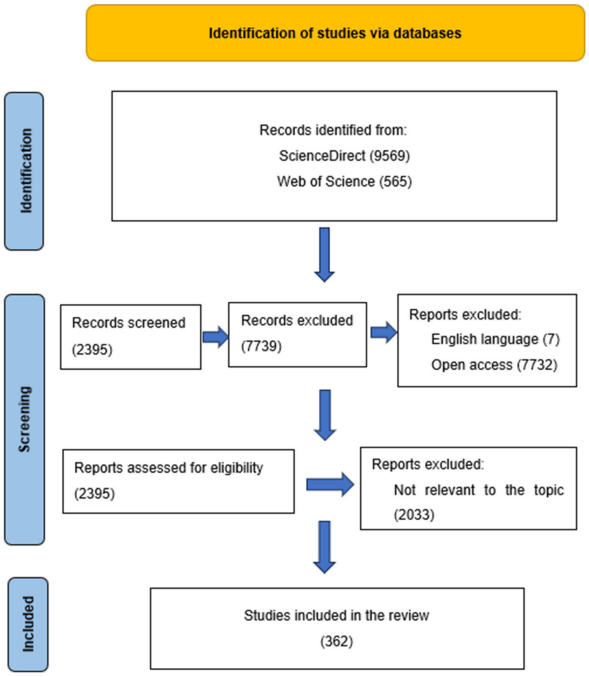


Figure 2. Flow diagram for the SLR process.

3. Results

Out of 2395 publications, 362 are related to energy refurbishment/retrofit in historical buildings. Because the search engine comes with any publication covering any part of the search term example, some publications are in historical buildings only, others are in energy efficiency only, etc. However, the 362 publications cover energy refurbishment/retrofit in historical buildings.

The publications on this topic started in 2000 with one publication, but in the following years, the publications on energy refurbishment/retrofit for historical buildings increased significantly to 71 publications in 2017 and 36 publications in 2022, as shown in Figure 3.

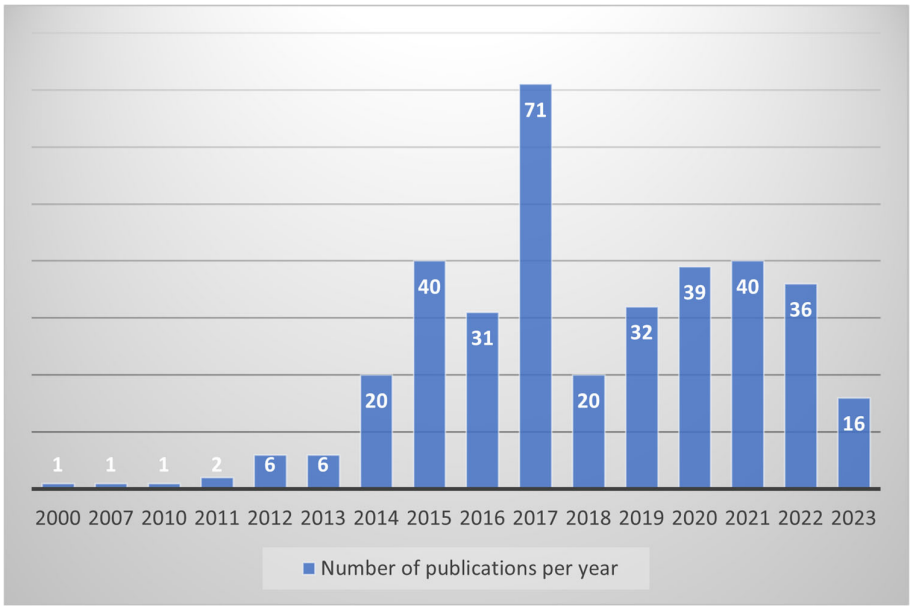


Figure 3. Number of publications on energy refurbishment/retrofit for historical buildings per year.

Most of these publications are in European countries, with 322 publications. There are 26 publications in Asia and a few publications covering this topic from North America, Africa, and South America, as shown in Figure 4. This topic is important in the European continent for many reasons, such as the high number of historical buildings on the continent, the continent's targets to achieve a zero-emissions economy, and the great efforts in reducing energy and emissions for existing buildings, including historical ones [27].

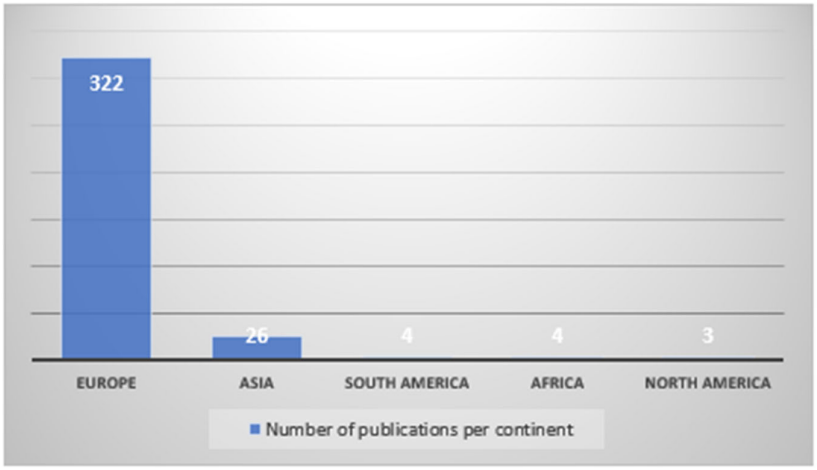


Figure 4. Publications in energy refurbishment/retrofit of historical buildings per continent.

As shown in Figure 5, Italy has the highest number of publications on energy refurbishment/retrofit for historical buildings in Europe, with 189, while the second country is the UK, with 20 publications in the area of historical building refurbishment/retrofit.

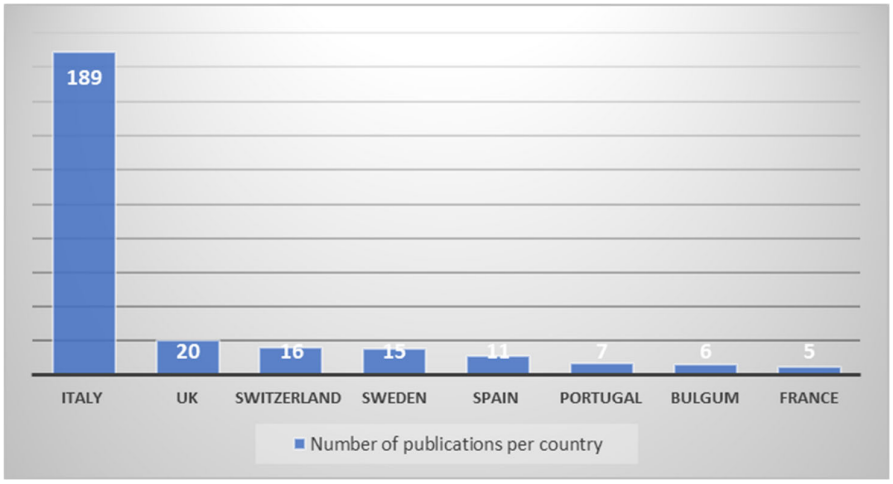


Figure 5. Publications in energy refurbishment/retrofit of historical buildings in European countries.

3.1. Publication Themes in Historical Buildings Energy Refurbishment/Retrofit

The 362 publications related to the energy refurbishment/retrofit in historical buildings covered different topics. The software VOSviewer version 1.6.20 was used to identify the main topics covered by the publications. Figure 6 shows the results from the software. The boldness shows the frequency of the term in the literature; the bolder and thicker terms are more frequent. Methodology, environmental impact, heritage buildings, thermal performance, and residential buildings are some of the most frequently used terms in publications regarding energy refurbishment/retrofit in historical buildings.

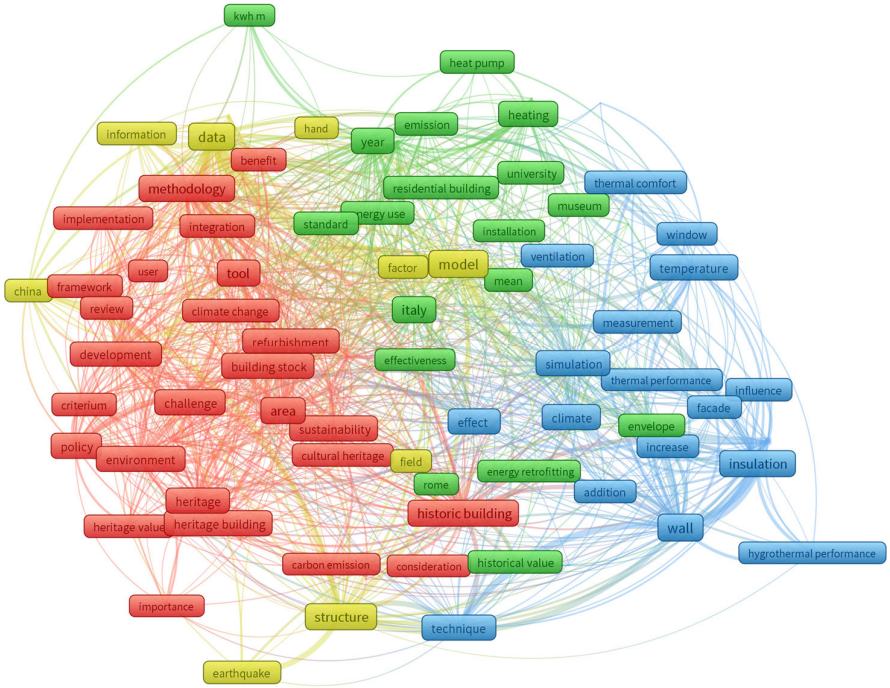


Figure 6. The energy refurbishment/retrofit of historical building publications' topics.

A deep analysis of the publications on energy refurbishment/retrofit of historical buildings showed that some publications focus on suggesting specific interventions to

improve historical buildings' energy efficiency and then measure the impact of these interventions. Other studies suggest different methodologies, tools, and processes to improve energy performance in historical buildings. Some studies measure the walls' performance in historical buildings and suggest insulation materials. Also, many studies implement pre-intervention studies to assess the current situation of historical buildings. Other studies covered different areas such as the use of software, renewables, WLCA, and other topics. Figure 7 shows the topics covered by the energy refurbishment/retrofit of historical buildings publications.

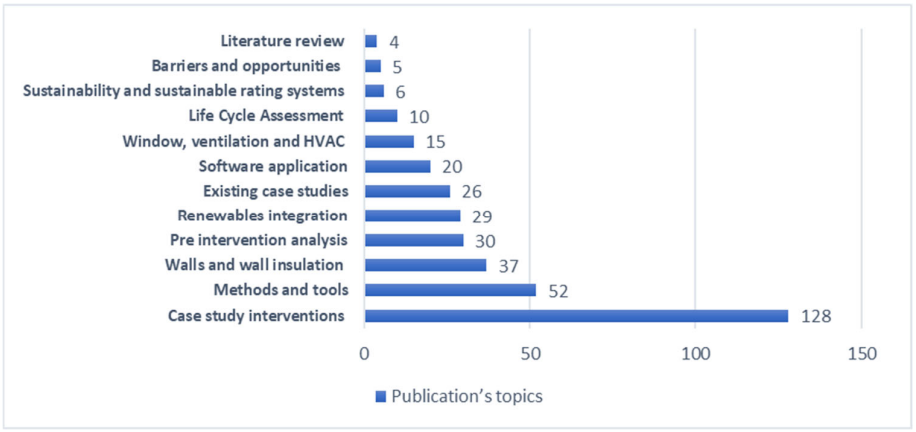


Figure 7. Publications in energy refurbishment/retrofit of historical buildings per topic.

Topics covered by the energy refurbishment/retrofit of historical building publications are discussed in more detail in the following section.

3.1.1. Case Study Interventions

The majority of the publications, 35%, selected historical buildings as a case study and found out the energy consumption baseline either via simulation or calculations, then suggested refurbishment alternative/s, applied them to the case study, and then calculated or simulated the intervention outcomes in energy/emissions savings. In some cases, the cost of the interventions and the payback periods were calculated as well. Energy assessment is a tool used to analyze the main contributors to energy consumption and carbon emissions; therefore, the suggested intervention can mitigate these areas [28]. Most of these studies identified the baseline consumption of the case study detailing the main contributors to the energy consumption, and after implementing the retrofit interventions, the impact of the interventions on those main contributors was assessed.

As shown in Table 1, the publications discuss case studies' interventions, selecting a variety of buildings, such as educational buildings, residential, and public buildings. The majority of the interventions were upgrading the fabric and the HVAC, while different software was used to calculate the baseline and the interventions' impact. In addition, the outcomes of implementing the suggested interventions were between a 34% and 80% reduction in energy consumption.

Table 1. Some of the publications discuss case studies' interventions.

The Study	Building Type	Suggested Interventions	Simulation Tool	Outcomes
[29]	Office building	Upgrade the fabric and heating system	Master Clima	70% reduction in energy consumption—6-year payback period
[30]	School	Upgrade the fabric and HVAC system and add renewables	Trnsys 16	70% reduction in energy consumption
[31]	Museum	HVAC systems add renewables	DesignBuilder	45% reduction in energy consumption
[32]	Residential	Upgrade the fabric and HVAC system	ArchiEnergy	70% reduction in energy consumption payback period of 11 years
[33]	Residential	Upgrade the fabric and HVAC system and lighting	DOE-2.1e	81% 4–8 payback period
[34]	University building	Upgrade the lighting system—HVAC systems add renewables	Termus and Termus plus	40% reduction in energy consumption
[35]	School	Upgrade the fabric and HVAC system	WUFI Pro	34.1% reduction in energy consumption
[36]	Multi-use	Roof insulation	Designbuilder, and EnergyPlus	55% reduction in heating and cooling load
[37]	University building	Upgrade the fabric and HVAC system	WUFI® Pro	reduction of up to 92% in heating demand
[38]	University building	Upgrade the fabric and HVAC system to integrate renewables	Stima10-TFM	reduction of up to 60% of the energy consumption
[39]	Religious building mosque	Upgrade the fabric and lighting system HVAC	IESVE	70.75% reduction in energy consumption
[40]	Residential	Upgrade the walls and windows	Calculation	50% reduction in energy consumption
[41]	University building	Upgrade the fabric and renewables	Calculation	80% reduction in energy consumption

Some case studies, as described below, showed a significant impact of implementing some interventions in historical buildings by reducing energy consumption by 60%, 75%, and 79%. One piece of research measured the output of several interventions, including façade upgrades, window upgrades, changing lighting, and adding solar panels, to a university historical building in Seoul, Korea [42]. The simulation program DesignBuilder 2019 was used to evaluate the impact of the interventions [42]. The energy saving in this case study could achieve over 60% savings [42]. A study was implemented for a residential complex in Italy built in the 16th century to evaluate the effect of upgrading the building envelope and HVAC systems. EnergyPlus Version 3.1.0. software was used to calculate energy performance for the existing situation and then the after-intervention situation [43]. After the intervention, the simulation showed a significant reduction in energy consumption of 75% compared to the base case [43]. A detailed study of a public historical building in Italy confirmed that upgrading the lighting system has a significant impact on the energy consumption [44]. The case study was a university library, and

the suggested intervention is a sustainable lighting system comprising natural lighting, energy-efficient lighting, and a management control system [44]. The interventions showed a significant reduction in the building energy consumption, aligned with the improvement of users' experience [44].

3.1.2. Tools, Methods, and Decision-Making Processes

Another 52 publications suggested tools, methods, and decision-making processes to promote historical buildings' energy refurbishment. Some examples of these studies are discussed in the following section.

One study developed a methodology to help buildings' owners consider refurbishing their buildings, considering the energy efficiency, overall cost, and indoor air quality [45], while another study suggested a whole-approach methodology to retrofit buildings, considering the whole life impact, not only the operational energy/emissions [46]. And this approach considers conservation issues while enhancing the building's energy efficiency and reducing emissions [46].

Another interesting study suggested numerical methodology based on several previous pieces of research in the field of historical building retrofit [47]. This method can help predict the retrofit interventions' outcomes depending on previously collected data [47]. Simulation models are used to identify the current performance of the building and the impact of the interventions [47]. After that, the numerical method will be used to identify the most valuable intervention that will improve the building's energy performance with reasonable economic feasibility to be implemented [47]. Alternatively, some studies focus on specific types of historical buildings, such as a study that suggested a methodological approach to retrofit pre-1914 dwellings in Belgium [48]. There are three main steps to implementing this method. First, apply a typology analysis for the pre-1914 dwellings, which can be classified into four main types [48]. Second, apply field studies to assess the main important heritage feature of these typologies besides the energy performance [48]. Third, suggest different interventions for each type and use energy simulation to measure and evaluate the interventions' impact [48]. Another example is a study that suggested a method to consider historical building preservation requirements in energy retrofit plans in a vulnerable environment context [49]. The suggested method includes the following steps [49]. Firstly, evaluate the building architecture features that need to be preserved, the energy performance requirement, and any maintenance requirements [49]. Secondly, create a matrix that integrates the three factors [49]. Thirdly, develop a retrofit plan that enhances these three pillars [49].

3.1.3. Wall Composition and Wall Insulation

Walls and wall insulation materials were discussed in 37 publications, as well as their impact on reducing energy consumption in historical buildings. A considerable number of these studies discuss the impact of using new insulation materials in historical building contexts, such as Aerogel. The following studies provide examples. One study evaluated the use of thermal insulation material to improve the energy performance in historical buildings [50]. The suggested materials were Aerogel and vacuum insulation panels, and the advantage of these materials is their considerably thin layers with good thermal resistance [50]. When applying the suggested materials to an existing historical building, the case study showed a 35% improvement in thermal performance with a 30% reduction in energy costs [50]. Another study evaluated the use of Aerogel insulation material to improve the historical building's thermal performance [51]. The study found that Aerogel insulation has a remarkable thermal resistance with a reasonable thickness, which makes it suitable to be used in the historical buildings' context [51]. The main disadvantage

of Aerogel insulation is the high initial cost compared with other traditional insulating materials [51].

Some studies discuss the impact of external wall insulation on the architectural features of historical buildings and then suggest using internal insulation. One study evaluates the concerns about the wall insulation in historical buildings, mainly saving the building's valuable architectural features [52]. The study focuses on using internal wall insulation materials and discusses the barriers to using this insulation, such as the impact on the indoor space, impacting the walls' homogenous, and the application complexity [52]. Then, the study evaluates the performance of five different modern insulated materials in historical building applications [52]. Another study was conducted in Poland to suggest a thermal improvement for the envelope of a residential historical building [53]. The study started by evaluating the current performance of the envelope by measuring the thermal conductivity, identifying the thermal bridges, and measuring the airtightness [53]. It then suggested applying an internal insulation layer and using energy simulation to measure the performance of the walls. The results showed a reasonable improvement in the wall thermal performance and stabilization of the water content [53].

3.1.4. Preintervention Analysis

Many studies (30) described pre-intervention analyses, such as historical building criteria that promote energy efficiency refurbishment. Some of these studies evaluate the whole building stock and try to suggest retrofit plans, such as the following cases. One study suggested a methodological approach to identify the historical buildings in Perugia, Italy [54]. The main task of this research study was to categorize historical buildings according to their energy performance [54]. To accomplish this task, the research team used document information, field investigation, thermographic scans, and occupant surveys [54]. Five main categories of historical buildings were identified, and this is an important step in establishing a clear methodology to improve these buildings' energy performance [54]. An additional study was conducted in Sweden to evaluate the current situation of historical residential buildings in the country [55]. The main aim of the study was to give a better understanding of how to consider the heritage, social, and cultural value of these buildings when applying an energy-efficiency retrofit [55]. Primary data was collected to evaluate the current situation of the stock, such as the energy certification data, and the national registration data [55]. After analyzing these sources of data, the results showed that the residential stock can be classified into three groups: buildings that did not go through any kind of retrofit, buildings that had a light retrofit, and buildings that had a deep retrofit [55]. Then, three case studies from each category were selected to perform further research on the current energy performance [55].

On the other hand, some studies focus on a single-building situation. For example, one study evaluated the energy performance of the existing case study. The case study was a museum located in Italy [56]. The purpose of the study was to evaluate the energy performance, microclimate conditions, and different technical space needs [56]. The result was comprehensive three-dimensional energy modeling that can be used to suggest different retrofit plans to improve the case study energy performance [56]. Another study was performed to evaluate the structural stability and the energy performance of a historical building in Italy [57]. The study used two methods to evaluate the building's performance: in situ measurement and simulation, and the two methods yielded similar results [57]. This study aims to provide considerable data to evaluate any required interventions to improve this building's energy performance [57].

3.1.5. Renewable Integration

Renewable integration in historical buildings was reviewed by 29 publications. Different studies suggested different types of renewables to be integrated into historical buildings such as a ground source heat pump [58], solar [59], and biomass [60], while others suggested using a hybrid system such as using heat pumps and biomass [61] or heat pump and PV [62].

Three studies looked at the broader picture and tried to evaluate the use of renewables in historical building contexts, such as a study exploring the use of renewables in historical buildings through real case study examples. The study showed that the use of PV in historical buildings can be complicated, considering their impact on the building's appearance [63]. On the other hand, the use of heat pumps and other efficient HVAC systems can be more practical to be integrated into historical buildings as they do not compromise the architectural appearance of the buildings [63]. Another study came to a similar conclusion, showing that the use of heat pumps and geothermal systems is more practical in the historical building context [64]. Then, the study suggested two systemic approaches to evaluate the suitability of using PV in historical buildings [64]. Another study tried to suggest practical methods to integrate renewable energy with historical buildings without compromising the architectural features of these buildings [65]. The study concluded that each historical building should be evaluated on a case-by-case basis on whether it is practical to integrate renewables or not [65].

From another perspective, two studies suggested a method to integrate PV systems into historical buildings: the first study suggested a developed methodology to integrate solar panels into historical buildings to improve their energy performance [66]. This methodology was based on a successful previous project and then suggested different approaches to integrate solar panels that can be suitable for a wide range of historical buildings [66]. In the second one, a study suggested a guideline to integrate PV systems into historical buildings to reduce energy consumption and emissions [67]. The PV systems can be installed within the building or on the nearby landscape [67]. The study confirms that integrating PV systems can be affordable and applicable in the historical buildings context [67].

Different studies evaluated the impact of integrating renewables in historical buildings, such as a study that suggested the use of two renewable systems to improve a historical hotel's energy performance [68]. While a heat pump was used to reduce the heating energy consumption, a PV system was used to reduce the electricity consumption [68]. The results showed a significant reduction in energy consumption by 75% compared to the base building with a 5-year payback period [68]. Another study measured the impact of integrated geothermal HVAC systems in a historical office building [69]. Historical Building Information Modelling was used to build the building geometry, while EnergyPlus was used to evaluate the pre- and post-intervention impact [69]. The results showed that using geothermal as an energy source can reduce the building heating load by up to 70% [69]. A study was conducted to analyze the performance of hybrid heat pumps when integrated into a university historical building in Italy [70]. The two systems are the ground-source heat pump and the air–water-source heat pump [70]. Both systems complement each other; the ground source heat pumps can provide more than 250 MWh for heating the buildings, while the air–water-source heat pump can provide a similar amount of energy to cool the building during summertime [70]. Another research study was performed to measure the impact of using PV in a 150-year-old castle in Sweden [71]. The first option to integrate the PV within the building roof was excluded due to the impact on the historical feature of the building and also the overshadowing of the building roof [71]. Then, suggesting a landscape PV system, with two different sides, the results showed that using PV in one site

can provide all the energy used by the building yearly, while the other site alternatively has higher financial benefits [71].

3.1.6. Software Applications

Different software is used in calculating the energy and emissions for the historical building retrofit projects; the most used software is TRNSYS, which was used in these studies [72–86]. Another commonly used software is Energy Plus, which is used in these studies [36,87,88], and Design Builder, which was used in [89,90] studies, while IESVE is used in those studies [91].

Software applications in historical building energy-efficiency refurbishment are discussed in 20 publications. Historic Building Information Modelling (HBIM) software application in historical buildings retrofit is discussed by many researchers. One study showed how to use the HBIM software in implementing a sustainable retrofit for historical buildings [92]. The research identified the benefits of using the HBIM in historical building retrofits, which can be considered as the software can generate plans and perspectives for the existing buildings using laser scans, and the software can also run energy simulations and evaluate different interventions to improve the historical building energy performance [92]. Moreover, the result of the HBIM can be produced in readable engineering documents, which makes it easy to implement [92]. Another study evaluated the use of HBIM in modeling and then evaluated the performance of interventions in historical buildings [93]. The study examined the use of HBIM in a case study scenario where a renewable system was integrated [93]. The Facility Management within the HBIM can improve the overall control of the building's energy performance and enhance occupant satisfaction [93]. Additional research has developed HBIM to improve its performance to integrate system management and operation control to reduce energy consumption [94]. Another piece of research introduces the HBIM use in historical buildings' energy retrofit while assessing its performance [95]. Then, a critical evaluation of the software was performed, and this highlighted the gap [95]. Then, a new development was suggested to overcome these limitations [95]. Another piece of research highlighted the implementation of the HBIM to evaluate retrofit interventions in a historical house [96]. The study showed the different advantages of using HBIM by integrating the conservation requirements with energy performance requirements, as well as evaluating the time and cost of the interventions [96]. Along with this came the software's ability to store, analyze, and use the data during the design and operation phase [96].

An interesting study compared the results of two energy simulation programs in historical building retrofits, with these being TRNSYS 16 and Grasshopper/Archsim 2013 [97]. In the first stage, the two simulation software results were compared with the real base energy consumption of the building [97]. The results showed that TRNSYS results are more similar to the real performance with only a 1.9% difference, while for the Grasshopper/Archsim, the difference is 6.24% [97]. Then, the two software versions were used to evaluate the impact of two suggested interventions, which replaced the window and integrated PV [97]. For the first intervention, the software Grasshopper/Archsim gave more reliable results because the architecture features have a great impact on the software calculations, while the software TRNSYS gave more reliable results for the PV integration, as the software calculations depend on technical aspects of the building [97].

3.1.7. Existing Case Studies

The impact of applying interventions to existing case studies and then measuring their effect is covered by 26 publications. Some studies focused on the refurbishment process, while the majority monitored the refurbishment outcomes after a period of time.

The refurbishment outcomes are either measured (U value differences before and after the refurbishment) or simulated.

The detailed impact of the retrofit interventions was discussed in many studies. One study discusses a historic school building that went through different stages of an energy efficiency retrofit [98]. The result of the total process, which consisted of upgrading the windows, insulating the fabric, and integrating heat pumps, achieved about 67% of the school's total energy consumption compared to the preintervention performance [98]. Another project was designed to retrofit a historical school to reduce energy consumption and enhance users' thermal comfort [99]. The retrofit plan was to upgrade the building envelope and integrate a heat pump [99]. The results of the project indicated that the total school energy consumption was reduced by 67% from the pre-intervention situation [99]. An additional paper evaluated a retrofit project for a farmhouse in Southern Italy [100]. The project implemented several interventions to improve the building's energy performance [100]. External wall thermos plaster made of local natural materials was used, alongside replacing the HVCA system, and two solar thermal systems were implemented [100]. An energy simulation is used to measure the impact of the interventions, showing that the final energy consumption by the building is 22 kWh/m^2 year [100].

Many studies evaluated the post-intervention impact of using insulation materials. One research project evaluated the use of Aerogel insulation materials as a blanket, board, or render in historical building energy refurbishment [101]. The study evaluated the role of the insulation material in improving energy efficiency and thermal comfort. Existing case studies showed considerable improvements in the thermal conductivity of the fabric using Aerogel insulation materials [101]. Another study focused on evaluating the performance of an existing historical building that underwent a retrofit to improve its energy performance [102]. The interventions included adding insulating materials to the internal wall [102]. The selected material was a natural breathable material (hemp fiber panels) to minimize the risk of compromising the walls' breathability [102]. The result showed a considerable improvement in the walls' thermal performance [102].

The occupants' satisfaction was discussed by a few research projects, such as a study focusing on measuring the post-occupancy performance of a historical building refurbishment. It found that the in-operation energy performance, total life cost of the building, and occupant satisfaction increased significantly after refurbishment [103].

3.1.8. Windows, Ventilation, and HVAC

Windows/ventilation and HVAC upgrading used for historical buildings to improve energy efficiency were discussed in 15 publications. The opening impact on improving the energy performance in historical buildings was discussed in some studies. One such study suggested a ventilation methodology for a historical commercial building built in 1882 [104]. The methodology promotes natural ventilation by adding more openings and skylights to enhance thermal comfort [104]. The evaluation of the methodology builds on three parameters: energy saving, thermal comfort, and indoor air quality [104]. The energy used for cooling savings can reach up to a 40% cut-off compared with the current situation [104].

HVAC improvement in historical building retrofits was a focus of many studies. One study examined the alternatives for HVAC systems that can be used to improve historical building energy performance [105]. The study implemented the suggested system in five different hotels in five different locations [105]. Different variables were used to modify the HVAC system, such as changes in the airflow to the fans, reducing the damper working time, and changing the flow pumps [105]. Then, Polyvalent HP technology was implemented to reduce energy consumption, in addition to using sensible

heat recovery [105]. The implementation of these interventions showed that a considerable reduction in energy consumption can reach up to a 55% reduction compared to the current situation [105]. An additional study evaluated the energy performance and cost of different HVAC systems that can be integrated into historical buildings [106]. The study found that the delocalized water/air heat pump has a lower environmental impact and lower overall cost compared with all air systems and radiant systems [106]

3.1.9. Sustainability and Sustainable Rating Systems

Sustainability and sustainable rating systems for energy efficiency in historical building refurbishment are discussed in six publications.

One study confirmed that using sustainability rating systems such as BREEAM and LEED would enhance the decisions in historical building retrofits [107]. Using these rating systems can improve the retrofit process by addressing many aspects, not only energy efficiency, but also indoor air quality, using sustainable materials, and waste management [107], which was confirmed by another study that showed that the use of the LEED certification system in a case study of reduced energy consumption preserved the building's historical features and improved indoor air quality [108]. The study evaluated a historical building retrofit project that achieved LEED certification [108]. The certification is the Green Building Council Historic building, specific for historical building retrofit [108]. The certification requirements were used in the retrofit early design stages. The retrofit process was first to evaluate the condition of the existing building, mainly the structure's stability and the architectural features that need to be preserved [108]. Second, run an energy simulation for the building to measure the current baseline [108]. Then, suggest different interventions to improve the building's energy performance and evaluate these alternatives according to the performance and cost [108]. The output of the selected interventions was a 39% reduction in the building's energy consumption, and the building gained LEED silver certification [108]. A different study comes with incompatible results, by assessing the twelve commonly used sustainability rating systems and then evaluating these systems in historical building retrofit [109]. The study results showed that these systems could not evaluate the historical building performance, especially in the energy performance area [109]. Therefore, the study suggested creating a special rating system that can be used for historical buildings [109].

The other three studies showed the sustainable impact of the historical building retrofit, such as a study based on a literature review expressing that retrofitting historical buildings to improve their energy performance will enhance the sustainability development goals [110]. The study confirmed that retrofitting historical buildings and enhancing their functionality will reduce the carbon footprint compared to demolishing these buildings and building new ones [110]. Another study was performed to evaluate the historical city of Nablus, Palestine, which confirmed that the preservation of the heritage building can enhance sustainability by improving the environmental, social, and economic factors [111]. Courtyards, thermal mass fabric, and openings used in the historical building in Nablus were evaluated, and the results showed the advantages of using those passive design methods to improve the thermal and energy performance of the buildings [111]. The study concludes that heritage buildings should be preserved and reused to satisfy the users' needs, and also, the lessons from the vernacular architecture should be applied in modern architecture to enhance sustainability [111]. An additional study confirmed that the retrofit of historical buildings can promote sustainability's three pillars: environmental, economic, and social [112], in addition to reducing the negative impact on the environment by extracting new material, which promotes the circular economy [112].

3.1.10. Others

The historical building energy refurbishment literature review was discussed in four publications [10,27,113,114], and another five publications [115–119] covered historical building energy refurbishment barriers and opportunities.

3.2. WLCA in Historical Building Refurbishment Literature

WLCA is a comprehensive approach to measuring the environmental impact of products or services [16]. This tool evaluates the environmental effect of all process stages from raw material extraction and production (A1–A3), transportation (A4), construction (A5), use (B1–B7), end-of-life (C1–C4), and beyond the life (D) [16]. Figure 8 shows the different stages of the WLCA in the construction industry. The use of the WLCA in the construction industry is important to evaluate the building's whole-life impact and can also help designers and decision-makers to evaluate different alternatives to find the optimum ones for the environment [16].

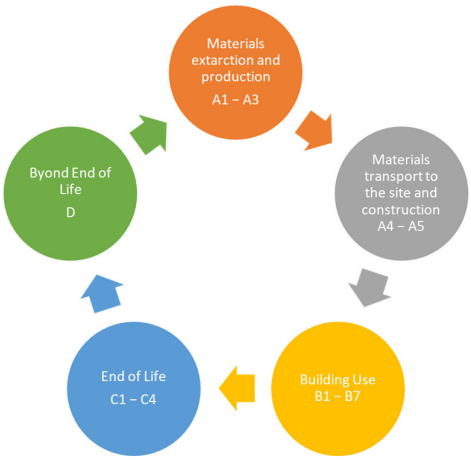


Figure 8. Whole life cycle assessment in construction.

Eleven publications discuss WLCA in the refurbishment and retrofit of historical buildings. The first was published in 2013. Table 2 shows the 11 studies, the case study selected, the country where the study was performed, and the stages of the WLCA that were considered.

Table 2. Refurbishment/retrofit historical buildings research covered by WLCA.

The Article	Case Study Building Type	Country	WLCA Stages Calculated							
			A1–A3	A4	A5	B6	B1–B5&B7	C1	C2–C4	D
[120]	Residential	Portugal	✓			✓				
[121]	Church	Italy		✓				✓		
[122]	Residential	UK	✓	✓		✓			✓	
[123]	Residential	Italy	✓	✓		✓				
[124]	Office	Portugal	✓	✓	✓	✓				
[125]	auditorium	Italy		✓	✓	✓		✓	✓	
[126]	None	-	✓	✓	✓					
[127]	Residential	China	✓	✓	✓	✓		✓	✓	
[128]	5 different buildings	Spain								
[129]	Residential	UK	✓	✓		✓	✓ not B7			
[130]	Residential	Germany	✓							

Description of the studies:

1. A study was implemented to evaluate a sustainable retrofit for an abandoned village in Portugal [120]. The study selected a single house as a case study and then applied the output to all village houses to obtain an estimation of the energy/carbon performance [120]. The suggested upgrades are structure upgrades, wall insulation, window upgrades, and integrated renewables [120]. The BEDEC 1 January 2013 database was used to calculate the embodied carbon for the proposed interventions [120]. The LCA calculations showed that the structure, cladding, and insulation have the highest environmental impact compared to the other building elements [120]. The output of the study confirms that using sustainable materials to retrofit historical buildings will improve energy consumption by 54% and reduce carbon emissions by 64% compared to the baseline [120]. It also showed the important rule for renewables of providing clean energy that can cover all building energy needs [120]. The study calculated the embodied and operational energy/carbon for the proposed interventions but did not account for the end-of-life impact; therefore, the whole retrofit life cycle impact was not considered. The database used for the embodied carbon calculation (BEDEC 1 January 2013) was developed for another country's circumstances, the authors' argument being that this happens due to a lack of nationally available data and the similarity between the two locations. Still, using a database that does not consider the country's industrial realm can be problematic and lead to imprecise results.
2. In this study, the LCA was calculated for three suggested thermal insulation materials (cork-extruded polystyrene (XPS), wood wool) [121]. SimaPro 7.3 was used to calculate the LCA. The LCA study was conducted with five different methods: IMPACT 2002+ v2.11, EDIP 2003 v1.04, EPS 2000 v2.07, and Re.Ci.Pe. Endpoint (E) v1.09/Europe ReCiPe E/A, and IPCC 2007 GWP 100a v1.02 [121]. All methods have different impact categories and different weighting factors [121]. This study compared five methods for calculating LCA, yielding contradictory results: three methods indicated that extruded polystyrene has a lower environmental impact, while the other two methods showed the opposite. This happens because different methods of calculating LCA have different parameters, boundaries, and calculation methods. This study confirms that establishing a framework to implement LCA in the construction field is essential. Although the XPS has a lower environmental impact in this case study, XPS is known as a rigid, closed-cell material [131]. Historical building construction materials are known as breathable materials that allow the movement of moisture; using a rigid material as an insulation material will compromise this ability and lead to condensation problems [132].
3. Another study calculated the total LCA and LCC for refurbishment materials applied on a grade 2 listed residential complex in Sheffield, UK [122]. The study aimed to compare different available refurbishment alternatives using multi-objective genetic algorithms to find the optimal alternative [122]. Also, the results of two different houses with different orientations were compared, as this can affect the operational energy/emissions. The refurbishment process focused on upgrading the houses' envelopes by adding insulation and upgraded windows [122]. The inventory of carbon and energy was used as primary data to calculate the embodied energy [122]. EnergyPlus was the software used to measure operational emissions [122]. The results of the study are that the embodied energy of the refurbishment was between 210 and 310 $kgCO_2/m^2$ [122]. And when comparing the LCA between a refurbished house and a non-refurbished and a new build, the results showed that refurbishment emits 20% more emissions than non-refurbished houses but saves between 30% to 45% of emissions compared to new builds [122]. The study compared the LCA of a limited

number of alternatives available to refurbish historical buildings. It compared the LCA for three different insulation materials and four different window compositions. Although the study evaluated a limited number of retrofit solutions, many thicknesses and alternative orientations were considered. The use of the multi-objective genetic algorithm helps in evaluating multiple results to find the optimal one.

4. A study was conducted to evaluate two insulation materials that LCA uses to insulate external walls in a historical house located in Cattolica, Italy [123]. The EcoInvent 3.1 database was used with two calculation methods, ReCiPe mid-point—Hierarchist (H) version—and Cumulative Energy Demand [123]. The construction–installation process (A5) and end-of-life stage (C1–C4) were not accounted for in this study as they were out of the study boundaries [123]. Also, maintenance, replacement, and refurbishment (B1–B5) were excluded, as the expected life spans of the materials will not require these steps [123]. Probabilistic methodology was used to overcome the uncertainty in the LCA calculation [123]. The result of the study showed that there is no considerable difference between the two suggested materials. This is because the operation energy and emissions during the operation phase are similar and this phase has a major impact on the whole-life assessment [123]. This study measured the LCA for two insulation materials and excluded different stages in the LCA calculation. The novelty of the study is using the probability distribution function to evaluate the uncertainty and sensitivity analysis for the input data. Highlighting an important issue, which is the high uncertainty of the data and performance of existing buildings, therefore, the use of uncertainty analysis and sensitivity analysis is essential in such studies.
5. Another piece of research focused on different retrofit scenarios in converting a historical house to an office building [124]. This study accounted for the environmental and financial impact of all suggested scenarios [124]. The interventions were to add an insulation layer for the walls and roof and upgrade the windows from single-glazed windows to double-glazed [124]. The impact of changing the insulation thickness and the occupation pattern was also examined [124]. The LCA calculation included the removal of the old materials and the construction of the new proposed materials during the operation phase, while the end-of-life phase impact was not included, as it is difficult to estimate the end of life for the building [124]. Also, the A1 to A3 were not included in this study [124]. The operation energy/emissions were calculated using EnergyPlus software, while the other phases' impacts were calculated using previous studies' data [124]. The result of the study showed that retrofitting the building using insulation materials can reduce the life carbon by 8% to 32%. And the roof insulation had the highest impact in reducing the environmental effect [124]. This study compared different scenarios to retrofit historical buildings and did not include the raw materials and end-of-life phases' impact. Consequently, the whole process of the life cycle impact was not measured. The distinguishing part of this study was calculating the removal of the old materials, which is not considered by many studies covering the historical buildings retrofit. Also, the study used the eco-efficiency analysis by considering both the materials with a low environmental impact and high annual savings.
6. For another study, the case study was a historical building named "Palazzo del Sedile" located in Basilicata, Italy [125]. The LCA was carried out with SimaPro Software and Ecoinvent3, ELCD, and Industry data as a database [126]. The suggested interventions were upgrading the building envelope, air conditioning, and lighting [125]. Both Designbuilder software and EnergyPlus were used to measure the output of applying those interventions in the case study [125]. This part was not performed by the re-

searcher but used previous work. A1, A2, and A3 were excluded from this study [125]. Using SimaPro Software, three different assessment methods were used: Cumulative Energy Demand, Eco-Indicator 99, and EDIP 2003 [125]. The three methods showed that the operation phase has the highest environmental impact [125]. When the study compared energy savings with the cost of each intervention, it found that lighting and air conditioning upgrades have the highest energy savings with lower costs [125]. This research measured the LCA for four different upgrades for a historical building but excluded the raw material extraction, the transport of materials to the factory, and manufacturing energy/emissions. Eliminating stages A1–A3 from the study calculation has a recognizable impact on the calculation of the LCA, as some research suggested that the A1 to A3 can reach up to 80% of the total embodied carbon [133]. The three methods used to calculate the LCA (Cumulative Energy Demand, Eco-Indicator 99, and EDIP 2003) are quite different; they use varied data; therefore, the output results are more challenging to read or compare.

7. A study focused on investigating the structural and environmental performance of using structural glass strips to upgrade timber floors in historical buildings [126]. The end-of-life stages were excluded from this study because of their low environmental load compared to the other stages and the limited information available to calculate the impact of these stages [126]. SimaPro 9.0 software was used with the EcoInvent v3.5 database for this study [126]. The result of the study showed that using structural glass strips to upgrade timber floors in historical buildings has a better environmental impact compared to other methods, such as reinforced concrete or cross-laminated timber [126]. This study had a limited scope in evaluating the environmental performance of upgrading historical building flooring and also excluded the end-of-life stages from the scope of the study. Two methods were used to calculate the LCA cumulative energy demand and non-renewable cumulative energy demand. Both methods calculate the energy demand and the global warming potential, which fulfill the study requirement.
8. A study was performed to evaluate the retrofit of the rammed earth heritage buildings in China [127]. The suggested interventions were adding insulation materials to the external walls and replacing the windows [127]. EnergyPlus software was used to calculate the intervention output [127]. The life cycle carbon emissions were calculated as the accumulation of the emissions of the material production, the operation, and the demolition phases [127]. Seven different types of wall insulation and four window types were investigated [127]. The research methodology comprised four main steps: firstly, calculate the thermal performance of the envelope; then, suggest insulation materials according to the standard and those commonly used; then, evaluate the thermal comfort of these interventions; and finally, analyze and evaluate the results. Among these different scenarios, applying the EPS insulation and 80 PW windows can reduce the house's overall emissions by half [127]. Also, the study showed that operational emissions account for about 90% of the total life cycle emissions for the selected case study [127]. The study investigated the life cycle emissions for external wall materials and windows for a rammed-earth house. A1 was excluded from the study, and other stages of emissions were estimated, such as the end-of-life emissions.
9. One study examined the use of positive energy districts in a historical area by applying different interventions in five buildings, including renewables, then assuming that those buildings are connected so the energy can be exchanged between them [128]. The research methodology had five main steps: onsite investigation, district energy modeling, suggesting interventions, performing LCA for the suggested interventions, and then proposing a road map for future retrofitting. Energy Plus was used as a

simulation tool to measure the effect of the interventions. The simulation was used to measure the impact of the external wall insulation, roof insulation, window upgrades, and lighting replacement [128]. The output of the study showed the importance of embodied energy/emissions and transportation, as both can contribute significantly to the building life cycle energy/emissions [128]. The study focused on achieving an energy/carbon balance at the district level. At the building level, the research applied interventions and calculated the overall performance with no details of the energy/carbon evaluations.

10. Another study measured the retrofit LCA for a pre-1919 Victorian house that underwent a deep retrofit to comply with passive house retrofit standards [129]. Also, the study used the same case study to compare six different retrofit scenarios, starting from a deep retrofit to a shallow one [129]. This research method involved calculating the baseline energy and carbon emissions of the case study, then suggesting six different retrofit scenarios, calculating the LCA of these scenarios, and comparing the results [129]. The Passive House Planning Package software was used to calculate the operational energy/emissions for the deep retrofit, while for the shallow one, Standard Assessment Procedure software, was used [129]. For all scenarios, One-Click LCA software was used to calculate the embodied energy [129]. The study considered the A1 to A3 and A4 to A5 and operational energy/emissions but excluded end-of-life emissions, as it usually has a low impact of less than 10% of the total life energy/emissions [129]. The study findings were that a building retrofit can reduce total carbon emissions by 59% to 94% [129]. When applying renewables to the building retrofit, the embodied energy increased significantly, but the operational energy was reduced. Also, using natural insulation materials reduces the embodied carbon by 7% to 14% [129]. The originality of the research lies in studying the LCA for different retrofit scenarios for the pre-1919 houses in the UK, which represent one of the most challenging house types to be retrofitted. The study evaluated different scenarios of energy/emissions performance, accounting for most of the LCA phases but excluding the end-of-life impact.
11. A study evaluating the overall performance of six insulating materials can improve the thermal performance of historical building envelopes [130]. The research aim was to perform a holistic approach to evaluate different insulating materials used in historical buildings [130]. The materials were perlite-filled bricks, wood fiber, cellulose, cork, mineral foam, and calcium silicate; all of these materials are naturally based and recommended to be used as internal wall insulation [130]. The six recommended materials were studied by implementing them in a real case study to evaluate their operational performance [130]. The holistic evaluation of these suggested materials is as follows: their impact on the building preservation requirement, their hygothermal performance, their environmental performance through the LCA, and the environmental payback period [130]. The study evaluated the A1 to A3 environmental impacts for the six materials, considering the Global Warming Potential, Ozone Depletion Potential, Acidification Potential of land and water, Eutrophication Potential, and Photochemical Ozone Creation Potential [130]. The results of the study showed that wood fiber, cellulose, and cork have a lower environmental impact compared to the other materials [130]. The limitation of this study focuses on the insulation materials' performance and counts the environmental impact for the production stage only.

A few studies covered the topic of the WLCA in historical building refurbishment. Most of these studies cover the impact of specific materials, such as insulation materials. All of these studies exclude some stages of the WLCA such as A1 to A3 and end-of-life

stages. No studies consider the D stage in the WLCA calculation while this stage can be an important factor in promoting the recovery of the materials.

4. Discussion

The retrofitting of existing buildings' stock, including historical buildings, is an urgent task to improve these buildings' functionality [134]. Historical buildings' energy efficiency refurbishment provides many opportunities but comes with many constraints. Improving the energy efficiency in these buildings is essential for many reasons, such as reducing the buildings' emissions, improving indoor air quality, and enhancing the building users' comfort [135]. Moreover, an energy efficiency retrofit can be an excellent chance to conserve traditional buildings and give them a new life while saving valuable architectural features [136].

In the current practice of the construction industry, building regulations and sustainability rating systems focus on operational energy/emissions. In 2021, it is estimated that embodied carbon accounted for 28% of global emissions [137]. The existing plans to retrofit buildings that consider only operational energy and emissions may result in an increase in embodied carbon [138]. Moreover, most of the research on residential retrofit focuses on operational energy and emissions, with fewer studies looking at the whole-life emissions' impact [139]. Hence, ignoring the embodied energy/emissions can lead to applying retrofit plans that increase carbon emissions [139].

A few studies covered the topic of the WLCA in the historical building retrofit. Most of the research focused on specific interventions and counted their life impact. The main limitation of these studies is that they count the environmental impact of limited process stages, such as the production stage. End-of-life stages' impact is not accounted for in many studies, and no study identifies this beyond the life stage influence. The concept of the WLCA is comprehensive and covers all the impacts of the process; therefore, any elimination of any stage can impact the results. Many studies use different databases and different methods, which lead to different outputs. This shows the need to establish clear and systematic approaches to implement WLCA. Also, much of the data related to the performance of the existing building, especially historical ones, is incongruous. Therefore, the need for uncertainty and validation of the data and then the results are essential in the energy retrofit of historical buildings.

Buildings consume energy and emit emissions throughout their life before construction (materials extraction, transport, construction), during their life, which is known as operational energy/emissions, and when their life comes to an end (demolition, recycling or reuse, and waste disposal). To reduce emissions and achieve a zero-emissions economy, all building life cycle emissions should be considered. More research is needed to study the life cycle of historical buildings to enhance retrofit decisions [140]. A whole life cycle assessment is essential for new builds and major refurbishment projects. If the target is to reach zero emissions in the construction industry, the whole building processes' energy/emissions should be counted and then reduced, and the remaining emissions can be offset [141].

For retrofit projects, there is a step that should be taken before the construction, which is the deconstruction of the old materials. These materials can then be transported to the disposal plant and processed, and the materials they contain can also be recovered during disposal, as shown in Figure 9. To enhance the path for the built environment to achieve the zero emissions target, all five steps, energy, and emissions should be counted from the early design stages for the retrofit. Then, suggest different alternatives to reduce the whole process's energy/emissions. Also, WLCA can be used to evaluate those different alternatives to select ones with a low environmental impact. After calculating the whole

process energy/emissions, improving the building energy performance will reduce the operational energy/emissions. Furthermore, integrating renewables, which can be one of the important factors in reducing building emissions, although applying renewables in historical buildings, is still challenging.

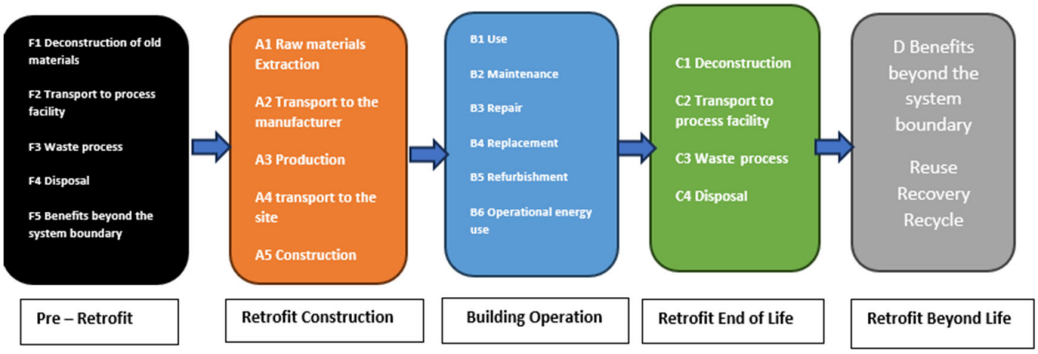


Figure 9. Building retrofit life cycle assessment.

5. Conclusions

Climate change has an astonishing impact on the creatures, the environment, and activities on Earth. The effort to reduce emissions and achieve a zero-emission target in all sectors including the built environment should be robust. Existing buildings, including historical buildings, are a major contributor to global emissions. Therefore, those buildings should be retrofitted to improve their energy performance. This paper implements a systematic literature review to examine the literature in the field of historical building energy retrofit. It identifies different scopes and studies performed in this field and also identifies the gap in the literature. In other words, the research has been performed, and research needs to be performed in the future.

The study identifies that starting from 2000, this topic was covered by 362 publications, with the pace increasing significantly in the last ten years. The majority of these studies were performed on the European continent, and Italy has the highest number of publications. The VOSviewer version 1.6.20 was used to identify the main topics covered by these publications. Methodology, environmental impact, heritage buildings, thermal performance, and residential buildings are some of the most frequently used terms in publications in the field of energy refurbishment/retrofit in historical buildings. A comprehensive study of the publications identified nine main areas for the publication. Most of the publications in building energy retrofit selected historical buildings as a case study and determined the energy consumption baseline, then suggested refurbishment alternative/s, applied them to the case study, and then calculated or simulated the interventions' outcomes in energy/emissions savings. Another topic covered is suggesting methods, tools, and approaches to implement historical building energy retrofits. Other topics, such as walls and insulation, pre-intervention studies, renewable integration, software applications, and evaluating the performance of existing retrofit projects, also had a considerable number of publications.

Then, the research analyzed eleven publications covering the use of WLCA in historical building energy retrofits. Most of these studies cover the impact of specific materials, such as insulation materials. All these studies exclude some stages of the WLCA, such as A1 to A3 and end-of-life stages. No studies consider the D stage in the WLCA calculation, while this stage can be an important factor in promoting the recovery of the materials. Therefore, more research to promote the use of the WLCA in historical building energy retrofits is needed, and this research work should consider the following:

- A whole life cycle assessment that accounts for the whole retrofit process's environmental impact. If the target is to reach zero emissions in the construction industry, the whole building process energy/emissions should be counted and then reduced, and the remaining emissions can be offset.
- Establish clear and systematic approaches to implement WLCA in historical building retrofits. This should include the system boundary, assessment methodology, and data sources.
- The need to perform uncertainty and validation evaluations for the data of historical building performance, and then, the results are essential in the energy retrofit of historical buildings.

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Abbreviation

WLCA	Whole Life Cycle Assessment
CO_2	Carbon dioxide
EFFESUS	Energy Efficiency for EU Historic Districts' Sustainability
3ENCULT	Efficient ENergy for EU Cultural Heritage
TABULA	Typology Approach for Building Stock Energy Assessment
SLR	Systematic Literature Review
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
HVAC	Heating, Ventilation, and Air Conditioning
IESVE	Integrated Environmental Solutions Virtual Environment
PV	Photovoltaic
HBIM	Historic Building Information Modelling
BREEAM	Building Research Establishment Environmental Assessment Method
LEED	Leadership in Energy and Environmental Design
TRNSYS	Transient System Simulation Tool
HP	Heat pump
LCC	Life Cycle Cost

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