

Review

An AI-Supported Framework for Enhancing Energy Resilience of Historical Buildings Under Future Climate Change

Büşra Öztürk ^{1,2,*} , Semra Arslan Selçuk ³  and Yusuf Arayıcı ⁴ 

¹ Graduate School of Natural and Applied Sciences, Gazi University, Ankara 06570, Turkey

² Department of Architecture, Selçuk University, Konya 42250, Turkey

³ Department of Architecture, Gazi University, Ankara 06570, Turkey; semraselcuk@gazi.edu.tr

⁴ Department of Architecture and Built Environment, Northumbria University, Newcastle upon Tyne NE1 8ST, UK; yusuf.arayici@northumbria.ac.uk

* Correspondence: busra.ozturk11@gazi.edu.tr or busra.ozturk@selcuk.edu.tr

Abstract

Climate change threatens the sustainability of historic buildings with increasing extreme weather events, making energy resilience critical. However, studies on energy resilience often lack forward-looking, holistic approaches. This study aims to develop a conceptual framework that includes how Artificial Intelligence (AI) technologies can support energy resilience in historical buildings with data-driven prediction and analysis to increase energy resilience against climate change. This study applied a methodology with four-stage qualitative research techniques, including a systematic literature review (PRISMA method), content analysis, AI integration, and conceptual framework development processes, in the intersections of historical building, energy resilience, and climate change. The findings reveal a significant research gap in the predictive analysis of the resilience of historic buildings and the integration of AI-based tools in the context of climate change. The proposed framework outlines a multi-layered system that includes data collection, performance analysis, scenario-based prediction, and AI-assisted decision-making, aiming to enhance the resilience of the building (including building envelope, thermal, and lifecycle analysis). Consequently, this study provides a theoretical and methodological perspective and proposes a scientifically based and applicable roadmap. It also highlights the potential of AI as a bridge between energy resilience and historical buildings in the face of a rapidly changing climate.

Keywords: artificial intelligence; climate change; computational architecture; conceptual framework; decision support systems; energy resilience; historical buildings



Academic Editor: Mojtaba Parsaee

Received: 29 July 2025

Revised: 11 August 2025

Accepted: 12 August 2025

Published: 15 August 2025

Citation: Öztürk, B.; Selçuk, S.A.;

Arayıcı, Y. An AI-Supported

Framework for Enhancing

Energy Resilience of Historical

Buildings Under Future Climate

Change. *Architecture* **2025**, *5*, 63.

[https://doi.org/10.3390/](https://doi.org/10.3390/architecture5030063)

[architecture5030063](https://doi.org/10.3390/architecture5030063)

Copyright: © 2025 by the authors.

Licensee MDPI, Basel, Switzerland.

This article is an open access article

distributed under the terms and

conditions of the Creative Commons

Attribution (CC BY) license

([https://creativecommons.org/](https://creativecommons.org/licenses/by/4.0/)

[licenses/by/4.0/](https://creativecommons.org/licenses/by/4.0/)).

1. Introduction

The frequency, severity, pattern, and seasonal cycles of weather and climate events are all altered by climate change, which has detrimental effects on several different areas [1]. As a result, one of the most significant problems of the twenty-first century is acknowledged to be climate change [2]. The IPCC [3] reports that the 20th century had the most exceptional rate of global temperature increase in the last millennium, with human activity mostly to be responsible. This increase poses a threat in the future as an increase in the occurrence and severity of severe weather conditions like heat waves, droughts, floods, landslides, cyclones, and heavy rainfall [4]. The IPCC (AR5) emphasized the urgency of the situation and warned that temperatures could increase by 2.6 to 4.8 degrees Celsius (°C) from present levels if emissions keep up their current

pace [1]. In this context, the existing building sector, which has a significant share in the increase in global temperatures and energy consumption, consumes more than 40% of the total energy used worldwide [5]. In addition, statistical data on the increase in greenhouse gas emissions from the building stock worldwide show an extreme increase since 1950 [6]. The European Union (EU) is taking important steps to address these challenges, including the Green Deal, which aims to achieve carbon neutrality by 2050 and a 55% reduction in GHG emissions by 2030 [7]. Following the EU Green Deal initiative, new agreements and strategies have been developed in various regions around the world. Examples of these agreements include Japan's Green Growth Strategy, South Korea's Green New Deal, the UK's Net Zero Strategy, and Australia's Net Zero Plan, among others, where various countries have worked to reduce their carbon emissions and energy consumption.

Cultural heritage assets, which reflect humanity's shared memory and identity, are also impacted by climate change. Cultural heritage includes tangible (structures, monuments, archaeological sites) and intangible (traditions, rituals, information systems) elements that have been produced by societies in the historical process, passed down from generation to generation, and carry universal value [8]. However, this heritage is becoming increasingly vulnerable and at risk from environmental stressors associated with climate change [9]. This makes it imperative to consider the effects of climate change on preserving cultural heritage and transferring it to future generations. Climate change leads to changes in temperature, humidity, and seasonal precipitation. Also, it increases exposure to extreme weather conditions that can hurt the buildings and substances of cultural heritage by accelerating biological, chemical, and mechanical deterioration processes [10]. The threats of climate change to cultural heritage are increasingly being examined, and studies are continuing domestically and globally [11]. Studies focusing on resilience in different fields and examining the latest technology for changing climate conditions are growing in this context.

Studies on resilience, climate change, and historical buildings have recently begun to be addressed in various contexts within a common cluster in the literature. Although studies on historic buildings and energy efficiency have been intensively studied, energy resilience studies are new. Some studies examine existing policies and regulations to strengthen cultural heritage's resilience to climate change [12–14]. Several studies in the literature focus on social, cultural, and environmental improvements of historic buildings based on upcoming climatic data and scenarios, and it is rarely seen that studies on building envelope and thermal resilience are conducted [15,16]. Furthermore, carbon neutrality and Life Cycle Assessment (LCA) studies on climate change and energy resilience in historic buildings are very limited. For example, Angeles et al. [17], while focusing on resilient and sustainable buildings through LCA analysis, appear to lack a contextual understanding of historic buildings. Angrisano et al. [18] emphasize the importance of natural materials in renovating historic buildings through LCA analysis. Obead et al. [19] reviewed the use of LCA analysis in the energy retrofitting of historic buildings. Studies focusing on reducing carbon emissions through LCA analysis of historic buildings within the context of energy resilience and considering future climate risks have not been adequately addressed in the literature. Also, the integration of artificial intelligence methods in cultural heritage and climate change-related studies has recently increased [20]. For example, in their study, Fiorini et al. [20] developed an AI-based monitoring method as a result of documenting material deterioration on the facades of the Palazzo Pitti building using the photogrammetric drone method and analyzing the data using the machine-learning method. Bakirman et al. [21] emphasized the efficiency of the deep-learning method using camera images in documenting and monitoring cultural heritage and its contributions to

the monitoring process. Heydari Torkamani et al. [22] demonstrate in their study that the use of neural networks in the study of the resilience of historical bazaars is effective in modeling and estimating qualitative features. Rahaman et al. [23] presented a methodology that includes urban ecological risk assessment by integrating machine learning into resilient environmental management for heritage-listed cities. However, studies on AI integration into protection and maintenance strategies regarding energy resilience in the context of climate change are still very limited in the literature.

Various studies have systematically analyzed the studies conducted on the changing climate and historical buildings. All these studies differ according to scope, scale, and time interval [11,24,25]. In these studies, researchers have aimed to document academic research about historical buildings and climate change and guide policymakers through the studies conducted. While Aktürk and Dastgerdi [26] examined resilience at the urban scale (cultural landscapes) through obstacles in their study, Crowley et al. [27] addressed the resilience of intangible values. Elena et al. [28] focus on the concept of resilience at the urban scale by addressing resilience in social, cultural, and economic subcomponents. According to the literature reviewed, studies on energy resilience have recently addressed this global issue in various regions, including Europe, Asia, the Middle East, and Africa, addressing various climate types. These studies demonstrate that each region seeks adaptive solutions to address its climate challenges. For example, studies in China address extreme humidity, Iran's studies address hot, dry climates, and Italy's studies address Mediterranean climates, seeking improvements to enhance energy resilience. However, a detailed examination of the resilience of historical buildings against climate change at both urban and building scales within the framework of the subcomponents of the concept of resilience and the establishment of a holistic evaluation framework in this direction has been identified as an essential gap in the literature. The literature review revealed that resilience is not categorized into specific classes but rather addressed within limited themes. This study details the concept of energy resilience under four headings and identifies the key components for developing the framework. Furthermore, a framework specifically for historic buildings, specifically multi-scale, adaptable to different geographies, and incorporating an AI-integrated decision support system capable of expressing resilience with numerical data, is lacking in the literature. Combining these elements strengthens the original and applicable aspects of the proposed framework and surpasses previous studies in the literature.

Historic buildings are highly vulnerable to changing climate risks, such as overheating and high humidity. In recent years, energy resilience has gained importance as a fundamental dimension in climate adaptation [16]. The preservation and resilience of these historical buildings are of multifaceted importance; however, traditional methods appear inadequate to manage these emerging risks. Increasing the energy resilience of historic buildings without compromising their heritage values is crucial [29]. Achieving this balance requires innovative approaches, and AI offers promising potential in this area. AI technologies, ranging from machine-learning algorithms to artificial neural networks and digital twins, are increasingly being used in climate modeling, energy optimization, and predictive maintenance across many sectors [21]. However, their integration in the analysis and management of the resilience of historic buildings against climate change has not yet been sufficiently explored.

This study addresses the problem of vulnerability of the energy resilience of historical buildings to climate change with a holistic approach. To address this problem, research addressed the following questions:

- Question 1: The cycles of climate over time and how they have changed until today (How these cycles have changed from the past to the present, according to

palaeoclimatological data, and how the rapid changes observed today are beyond natural cycles)

- Question 2: What are the differences in how historical buildings are affected by climate change compared to other buildings? (How differences such as materials, construction techniques, and conservation policies affect the level of risk)
- Question 3: What are the possible impacts of exposure of historical buildings to climate change? (Structural risks, aesthetic, and functional losses are assessed within the framework of climate parameters)
- Question 4: What are the various components of the resilience of historic buildings against climate change? (The concept of resilience is divided into subcomponents according to various factors)
- Question 5: To what extent do existing studies integrate AI-supported methods when addressing energy resilience under climate change? (While AI is used in various sectors and energy, studies suggesting its use in the context of future climate risk are limited)
- Question 6: How can AI methods assist in resilient and predictive decision-making to reduce the impact of climate change on cultural and historical buildings? (Providing various potentials such as data-driven risk analysis, forecasting with climate scenarios, optimization of resilience strategies, decision support systems, and early intervention)

With this approach, the study aims to (1) define the components of energy resilience in the context of historic buildings; (2) analyze current research trends and methodological gaps; and (3) identify shortcomings. It also aims to provide a framework that operationalizes AI tools for predictive assessment, decision-making, and early intervention. This study will develop a conceptual framework that examines the resilience of historic buildings from a multidimensional perspective and incorporates remediation and prediction strategies based on climate change and environmental risk factors using an AI-based system. The study's originality stems from its innovative contribution to risk management and protection studies related to the energy resilience of historic buildings, based on the integration of AI-based modeling, prediction, and decision support systems. The study is expected to highlight and open new perspectives on the need for scientific production in the literature on historic buildings and energy, also to consider energy resilience in the context of climate change.

This study analyses the projected effects of climate change on historic buildings with a multifaceted strategy. It addresses the significance of creating climate-resilient strategies for these buildings' physical, structural, and cultural integrity. The theoretical and methodological approach to be followed within the scope of the study is detailed in the flow chart in Figure 1.

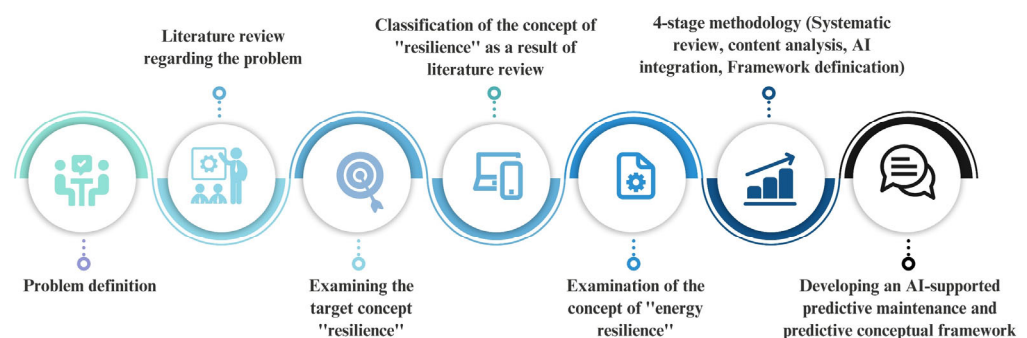


Figure 1. Flow chart of the literature review, content analysis, and conceptualization process.

2. Literature Review

2.1. Historical Cycle of Global Temperatures

Research on climate shows that the Earth's climate has naturally cycled and varied over thousands of years. Milankovitch cycles, orbital axis tilt, and precession changes are the main factors shaping the changes in glacial and interglacial periods [30]. These cycles affect the climate in varying periods between approximately 20,000 and 100,000 years and affect the temperature changes in the long term. According to climate data, although the climate during the Holocene period is considered warm and stable (compared to the glacial period), changes like the Little Ice Age and the Medieval Warm Period occurred [31]. Although these changes observed throughout history reveal a dynamic and continuous structure of the climate, it is also necessary to examine the changes observed as a result of human interventions in this process.

With the industrialization that started during the Industrial Revolution (1850), the increasing use of fossil fuels, and the rise in greenhouse gas density, the increase in emissions has caused an unexpected increase in global temperatures from its historical course. According to the IPCC [32], an approximately 1.1 °C increase in global average surface temperatures was observed between 2011 and 2020, compared to the 1850–1900 period (Figure 2). In addition to this increase in temperature levels, climate frequencies are affected, causing significant changes in precipitation regimes, sea levels, and extreme climate events. Changes in all these climatic parameters may cause material deterioration, changes in indoor comfort, and destruction because of disasters at the urban scale by affecting heat-related expansion, freezing, and thawing cycles on historical buildings in the long term. For this reason, it is essential to build conservation and adaptation strategies for a changing climate according to future scenarios rather than past trends and to take precautions.

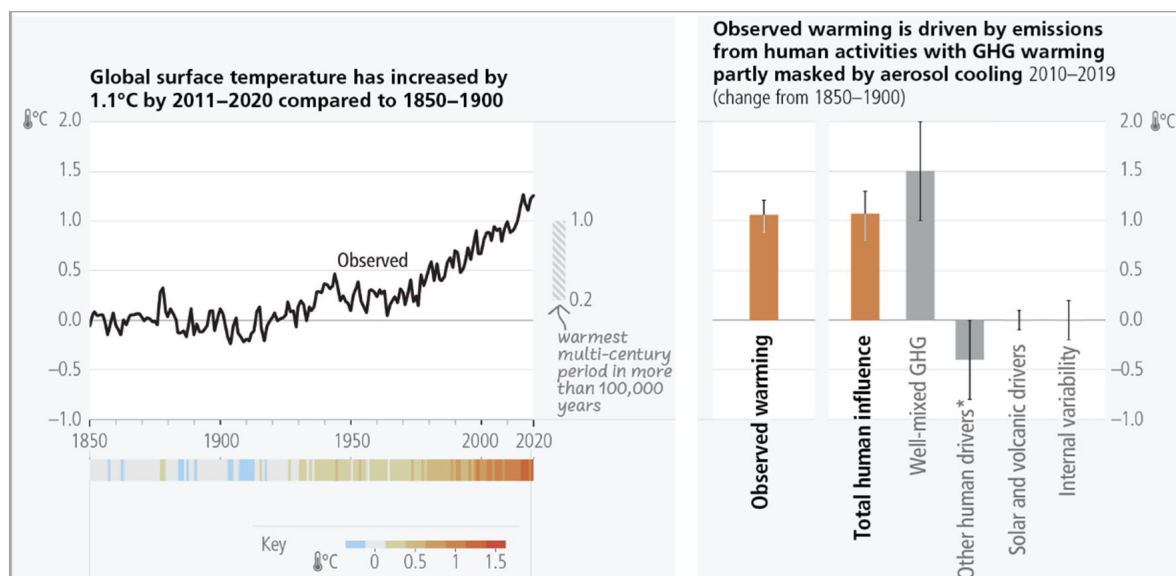


Figure 2. Changes in global surface temperature and emissions (* Other human drivers are predominantly cooling aerosols, but also warming aerosols, land-use change and ozone) [32].

2.2. Climate Change and Climate-Related Risks

Climate change is defined by the United Nations Framework Convention on Climate Change [33] as climatic changes observed in comparable periods, both directly resulting from natural processes and indirectly because of human activity impacting the atmosphere's composition worldwide. Gradual variations in temperature, precipitation, air humidity, wind speed, sea level rise, and extreme occurrences are all signs that climate change continues to affect social and environmental attributes in various ways [34].

Between 2011 and 2020, the global surface temperature increased by 1.1 °C over 1850–1900 due to human activity, primarily greenhouse gas emissions. The global surface temperature increased by 0.99 [0.84 to 1.10] °C over the first two decades of the twenty-first century (2001–2020) compared to 1850–1900. Global surface temperature, which has been increasing particularly since 1970, has rapidly increased in the last 50 years. The IPCC [3] projects that, in the direst scenario, the global surface temperature will have increased by more than 2.6–4.8 °C by the end of the twenty-first century compared to 1886–2005. With this increase in temperature, extreme climate events are expected to occur more frequently and cause various region-specific extremes. Human-induced climate change has already impacted several weather and climate extremes in every location. This has resulted in several detrimental effects on human health, economics, society, and food and water security, as well as losses and harm to both people and the environment [30–32].

According to the IPCC (AR6), GHG emission scenarios with various climate policies are derived using Shared Socioeconomic Pathways (SSPs), which are climate change scenarios with anticipated socioeconomic worldwide changes by 2100 [1]. These scenarios incorporate land use, socioeconomic assumptions, levels of climate mitigation, and air pollution controls for non-CH₄ ozone precursors and aerosols. The five Shared Socioeconomic Pathways (SSP1 to SSP5) are created to address various climate change mitigation and adaptation challenges. SSPs assess climate impacts, risk, and adaptation for future exposure, vulnerability, and adaptation challenges. CO₂ emissions in the high and very high GHG emission scenarios (SSP3-7.0 and SSP5-8.5) are roughly double what they are now in 2050 and 2100, respectively. The medium GHG emission scenario (SSP2-4.5) shows CO₂ emissions remaining at current levels until mid-century. The very low and low GHG emission scenarios (SSP1-1.9 and SSP1-2.6) envisage CO₂ emissions falling to zero between 2050 and 2070, respectively, followed by various detrimental net CO₂ emissions (Figure 3).

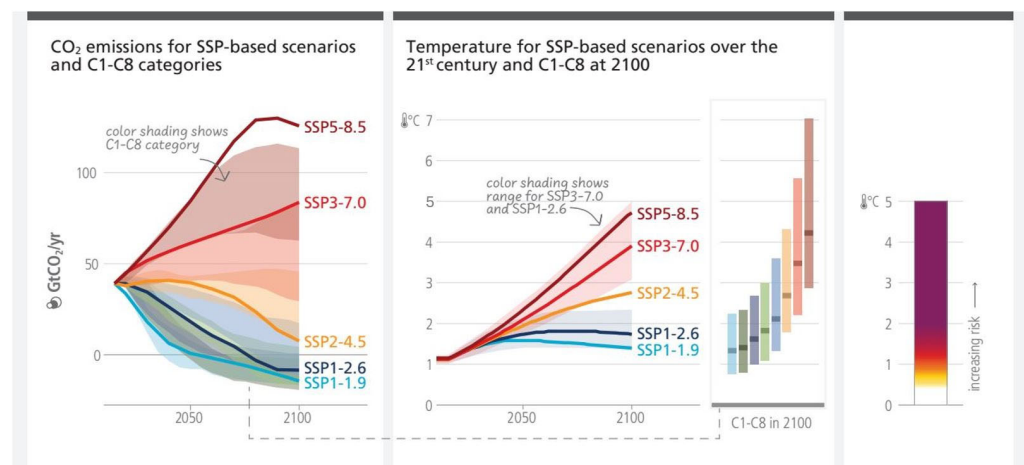


Figure 3. 21st-century temperature changes for SSP-based scenarios and CO₂ emissions for C1–C8 and SSP-based scenarios [32].

The Paris Agreement aims to limit the rise in the world's temperature caused by human-induced GHGs to less than 2 °C compared to pre-industrial periods and to keep the increase to 1.5 °C. Furthermore, its goal of achieving carbon neutrality by 2050 is important in the fight against climate change. This agreement encourages countries to pursue long-term, low-greenhouse gas-emission, resource-efficient development strategies to better frame efforts toward this long-term goal. In this context, the SSP1-1.9 and SSP1-2.6 scenarios, which are compatible with the Paris Agreement's goals of limiting temperatures to 1.5–2 °C, are important in taking measures to achieve targeted low emissions and mitigate global warming effects by 2050. Climate change causes serious harm to terrestrial,

freshwater, cryospheric, coastal, and open ocean habitats, as well as losses that are becoming more irreversible. Biological responses, such as seasonal timing and geographic location alterations, are frequently insufficient to address recent climate change.

2.3. Climate Change and Effects on Cultural Heritage

Cultural heritage sustainability and protection are seriously threatened by climate change. The United Nations Educational, Scientific and Cultural Organization (UNESCO) identified this situation as a danger to cultural heritage in a report published in 2007 and published a policy document in 2008. These developments have paved the way for increasing academic and applied research. More recently, the International Council on Monuments and Sites (ICOMOS) report [8] offers a thorough analysis of the primary causes of climate change, the impact mechanisms of these factors, and the possible consequences on cultural heritage in light of expert opinions.

Climate change, population growth, and urban expansion are becoming a primary driver of increased vulnerability in historical districts [33]. Climate change's effects on cultural heritage and natural resources are multidimensional and manifest primarily through sudden and long-term changes in environmental conditions [34,35]. These impacts include flooding, sea level rise, coastal erosion, changes in air and sea temperatures, fluctuations in humidity, increased frequency and severity of extreme weather events such as hurricanes, storms, and droughts, processes leading to physical erosion of building materials, and transformations in soil and sediment dynamics [36,37]. The rising incidence of severe weather conditions brings physical risks and socioeconomic, cultural, and environmental challenges (Table 1).

Table 1. Impacts of climate change risks on historical buildings [8,36].

Climate Change	Risks	Potential Impacts on Cultural Heritage
The rise in global temperatures	• Extreme temperatures and heat waves	Social Urban neighbourhoods and historic buildings are abandoned; coastal metropolitan areas are evacuated because of soil erosion.
	• Flooding along the coast	Economic and/or environmental Decline in travel and associated activities; rise in energy consumption, and financial losses.
	• Drought	Physical Material and structural deterioration (cracking, splitting, fungal growth, etc.).
	• Temperature and humidity fluctuations	
Rise in heavy rainfall events	• Flooding or landslides in rivers or inland areas	Social Loss of identity and shared values, eviction, and progressive desertion as a result of inadequate comfort.
	• High levels of precipitation and cold waves	Economic and/or environmental Increased energy demand and financial losses for insurance firms and/or estate administrators.
	• A rise in the humidity of the air	Physical Material decay, moss formation, and structural damage due to increased load.
Rise in severe storms occurrences		Social Loss of identity and shared values because of eviction and abandonment
	• High wind gusts	Economic and/or environmental Financial losses for insurance companies and/or estate administrators
		Physical Cultural heritage that has been partially damaged, lost, or destroyed

Historic buildings constitute a significant portion of the building stock in many countries worldwide. For example, in Europe, the historic building stock accounts for a significant 25 per cent [38]. However, when the buildings in Europe are analyzed, it is seen that more than 14% of them were built before 1919, 12% between 1919 and 1945, and 40% before 1960 [39]. Furthermore, most of these historic buildings have not had energy conversions. Residential buildings built between 1945 and 1969 had walls with an average U-value of 1.39 W/m² K, whereas residential structures built before 1945 had walls with an average U-value of 1.45 W/m² K [7]. This indicates that historic buildings typically use more energy

than contemporary buildings [40]. In addition, while the heating load decreases in winter due to the increasing global temperature, historical buildings face increased cooling load or uncomfortable conditions in summer [41]. Careful balancing of conservation and energy is required in unpredictable temperature increases [42]. The effects of climate change can cause wear and destruction in the texture of historical materials and prepare the ground for developing fragile properties. In addition, many techniques used in the context of climate adaptation for today's modern buildings cannot always be applied within the legal requirements to preserve the original features of historical buildings. Therefore, the climate adaptation process for historical buildings should be handled in a multidimensional approach to increase users' comfort and energy performance qualities, prioritizing the protection of cultural value. These changes in energy consumption in historic buildings emphasize the necessity of mitigation and adaptation measures, as stated in the IPCC [3]. In this context, studies on the improvements of the building envelope, which is a buffer between the inner and outer layer, and the integration of HVAC systems to provide indoor comfort are implemented with limited interventions without damaging the cultural value [42]. In addition, Historic England's 'Adapting Historic Buildings for Energy and Carbon Efficiency' [43] report recommends replacing systems in historic buildings with low-carbon systems such as mechanical ventilation, heat recovery mechanisms, heat pumps, and, in some cases, photovoltaic and solar panels may be acceptable.

3. Concept of Resilience and Components

The concept of resilience has become a critical focus in architecture to develop solutions to the issues brought on by industrialization, increasing urbanization, climate change, and socioeconomic disruption [44]. It means the ability to maintain its functioning and protect its components against any factor or hazard [45], to deal with risk, to recuperate by renewal and to adapt to similar risks, and to respond or reorganize by maintaining the capacity to learn and transform [46]. One of the most important goals of resilience is to return to the pre-risk situation and adapt and collaboratively adapt to changing conditions [47]. Furthermore, cultural, social, economic, and environmental aspects using collective memory and local knowledge are important learning and research processes that must be considered when developing resilience to extreme events [14].

Research on resilience can offer important solutions to ensure cultural heritage sites' sustainability and intervene promptly [48]. The number of studies investigating the concept of resilience and its application to various disciplines has increased in recent years. When these studies are examined, it is seen that resilience is analyzed in various aspects, such as urban planning, climate change, disaster and risk management, and nature conservation, according to changing developments at various scales [49]. For instance, Elena et al. [28] examined resilience using social, economic, and cultural criteria. Multidimensional methods that include developing resilience against climate change impacts, providing adaptation, and developing risk management by adapting to potential risks gain importance at this point [50]. Within the scope of this study, four different resilience dimensions of historic buildings that need to be developed due to climate change exposure have been classified. These categories are climate disaster resilience, energy resilience, sociocultural resilience, and economic resilience (Figure 4).

These four resilience components directly align with and support international policy goals on sustainability, cultural preservation, and climate adaptation. For example, the first component, resilience to climate disasters, aligns with the Sendai Framework for Disaster Risk Reduction (2015–2030), UN Sustainable Development Goals (SDGs) 11 and 13, and the EU Strategy on Adaptation to Climate Change. The economic resilience component is aligned with the Paris Agreement and the OECD Resilient Economies Principles. The socio-

cultural resilience component aligns with the UNDRR Resilient Cities and the Hangzhou Declaration. Energy resilience, the basis of this study, is aligned with IPCC AR6, the Green Deal, the Paris Agreement, and UN Sustainable Development Goals 7, 11, and 13 regarding building envelope and thermal resilience. Carbon resilience aligns with the European Green Deal's goals of neutralizing the building stock and increasing energy efficiency. The holistic energy resilience subcomponent is fully aligned with the European Framework for Action on Cultural Heritage and the ICOMOS Climate Change and Heritage reports. These policies strengthen the applicability and scalability of the proposed framework in the context of resilience development.

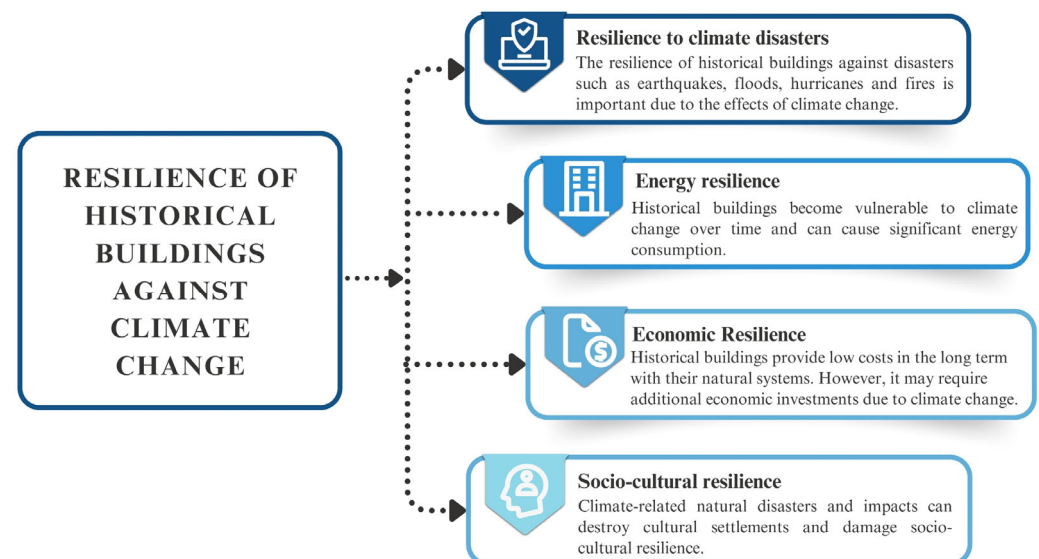


Figure 4. Classification of the resilience of historic buildings against climate change.

3.1. Resilience to Climate Disasters

Due to climate change, heritage sites are exposed to gradual changes in climatic phenomena (variations in wind speed, temperature extremes, air humidity, precipitation patterns, sea level rise, etc.) and climatic risk factors. Therefore, the literature's work is expanding quickly on climatic risk factors and their impact on cultural heritage [12,14,34]. In the studies of organisations such as ICOMOS, UNESCO, and ICCROM on the preservation and sustainable administration of cultural heritage, the focus is on natural disasters and assessing man-made threats. Through a series of guidelines published by these organisations and regular meetings, natural and anthropogenic disasters and risks to natural and cultural heritage sites are assessed, and mitigation methods are developed [51].

In assessing climate change impacts, selecting key climate variables like sun radiation, humidity, precipitation, wind, and temperature is significant, highlighting each factor's impacts [52]. For example, temperature changes and irregularities are among the main factors affecting the deterioration process of building materials. Especially in porous stone materials, water trapped in porous stone materials causes cycles of freezing and thawing according to temperature fluctuations, causing sugaring, thermoplasticity, and physiological and biological deterioration. Humidity, another climate parameter, can cause significant deterioration in the components and materials of historic buildings. Moisture-induced degradation is generally seen as biological degradation, corrosion, abrasion of metals, and chemical degradation due to freeze–thaw and thaw–crystallization cycles [53]. Precipitation causes changes in rainfall regime and intensity according to changing global climate patterns, causing chemical and biological erosion and threatening cultural heritage sites by causing flood risk [54]. Wind, another climate parameter, is an important climatic factor that causes various effects on heritage buildings. The wind's direction, strength, and

intensity can cause corrosive or destructive effects on the building material, depending on the particles driven into the surrounding environment and their proportions [55]. In addition, changes in solar radiation can cause damage to heritage buildings through both direct and indirect effects. Solar radiation damages include local overheating, discoloration of materials, cracks, and loss of effectiveness of material binders. In addition, ultraviolet and visible light can cause photo-oxidation and discolouration of heritage materials such as stone and wood over time [53,56].

Climate change increases the frequency of extreme events in the climate by altering the frequency and pattern of climate parameters. Therefore, to reduce the impact of climate change on historic buildings, it is critical to adapt to future changes. According to the IPCC [3] report, catastrophe risk management and climate change adaptation can boost resilience while lowering exposure and vulnerability. However, it is seen in the literature that studies on practical adaptation measures in tangible cultural heritage remain limited and piecemeal. In this context, it is crucial to consider the effects of climate change, material and collection degradation, and the processes of natural disasters through in-depth climate projections and to develop adaptive solutions. Therefore, adapting existing technologies to climate impacts and developing new technologies to reduce the frequency of environmental factors will contribute significantly to this issue [53].

3.2. Energy Resilience

Energy resilience is defined as “the ability of an energy system to contain, respond to, overcome and surpass disruptions caused by a shock in economic, social, environmental and institutional terms, resulting from the capacity to learn to adapt to change” [57]. This definition emphasizes that the risks that trigger resilience should be addressed in the context of technical systems and the holistic dimension of energy risk sources. Unexpected risks arise as a result of climate change, and vulnerable historical buildings face holistic energy resilience issues such as increased energy consumption and environmental impact. On the other hand, there are only ten years left to keep global warming below 1.5 °C, and even a half-degree increase beyond that would significantly increase the impact of risks like drought, extreme heat, flooding, and poverty for hundreds of millions of people, according to the world’s top climate scientists [58]. Therefore, the need for energy-efficient retrofitting historic buildings is becoming increasingly important [59]. Historic buildings were initially designed according to the environmental influences of their time, considering local conditions. However, nowadays, in the face of a dramatically changing climate, preservationists cannot take into account the materials and hygrothermal characteristics of the building. Against this problem, it is essential to investigate and simulate the current thermal behaviour of the building and the performance of the building envelope components and to propose strategies by identifying microclimatic conditions [60].

While climate change has been widely addressed as an environmental issue, its impact on energy consumption in buildings has not been sufficiently embraced and fully understood [61]. However, there is a strong relationship between climatic conditions and building energy performance and energy use. Due to changing indoor environmental conditions caused by climate change, energy performance analyses of historic buildings are expected to increase cooling load requirements and decrease heating load requirements [62]. Therefore, it is important that interventions and designs to develop sustainable and climate-resilient buildings take climate change into account throughout their lifecycle [63]. In the studies, it is seen that two types of methods, active and passive strategies, are applied in energy-efficient retrofitting of historical buildings.

Passive Strategies include the use of natural ventilation that provides passive cooling in climatic zones with high temperatures for long periods, the use of the courtyard system,

behavioral measures adopted by users, improvements achieved on the building envelope (insulation, thermal inertia, windows, air sealing, prevention of thermal bridges, shading devices, etc.) [64,65].

Active strategies include renewable energy technologies (photovoltaic and solar thermal systems, etc.), efficient lighting, electrical equipment (low-consumption high-efficiency lighting, etc.), high-efficiency heating, cooling, and ventilation (HVAC) systems, and the use of smart consumption and control devices that optimize energy consumption based on the adaptable comfort conditions of the users [64–66].

Various methods exist for retrofitting energy efficiency in historic buildings against climate change. However, retrofitting works on the building envelope is the most effective method for both adaptation and energy-efficient improvement of buildings [67]. The building envelope causes most energy losses in buildings, caused by heat transfer. The building envelope affects the building's thermal comfort, which controls indoor temperatures. Therefore, it is important to renovate or design the building envelope with optimal interventions to decrease energy consumption [68]. There are legal and technical challenges in the energy-efficient renovation of historic buildings due to restrictions on the minimum intervention scale without damaging their unique and cultural values. In addition, making compatible and recyclable decisions is important to preserve the original materials in interventions. In interventions for historic buildings, methods suitable for the components of the building are addressed with various approaches in the literature [64].

Walls: the exterior walls are among the building's most crucial features, where the characteristic features are dominant. Therefore, although intervention on the exterior wall surface is generally not recommended, plaster applications from phase change materials are considered more appropriate to increase thermal inertia in areas without original surface details on the interior wall surfaces. However, insulation material is supposed to be used. In that case, it is expected that the material should be breathable, and using materials such as natural fibres with high vapour permeability will allow air and moisture vapour to pass slowly, minimising condensation and moisture problems. In literature, mineral wool and thermal insulation plasters are the most often used materials. Used to add or replace insulation [64,65].

Windows: While the preservation of glass and frames is recommended as they are one of the original qualities of the building, it is emphasized that attention should be paid to important problems such as air tightness. There are two most common methods of window retrofit. The first method is retaining the original material, repairing the system, reducing air tightness, and adding a high-performance secondary window next to the old one. The second method is to replace the original window with a new window with high performance and a look that does not damage the historical value [66].

Floors: the original floor materials of the building should not be removed immediately due to various damage. When it is necessary to change the floor material, minimal interventions can be made. The most common intervention in ground improvements is the addition of insulation, and materials such as cellulose, hemp, and wood fibre are most used [64–68].

Roofs: minimal intervention is recommended as the original roof materials and components of the building are designed to be ventilated and watertight according to the climatic characteristics of the period. However, in literature, mineral wool and cellulose are the most used materials to replace or substitute insulation where intervention is required [66].

When the studies developed on energy resilience are examined, it is seen that there should be four important study groups, including building envelope improvement (active and passive methods) to assess the building's energy performance, providing thermal comfort according to changing climatic conditions for user comfort, reducing increasing

carbon emissions, emission reduction practices to reduce climate change effects, and studies that develop a holistic resilience framework and produce scoring with multidimensional building performance analysis (Figure 5). These subheadings present an approach that aims to increase historic buildings' energy efficiency and reduce their environmental impact by addressing different aspects of energy resilience.

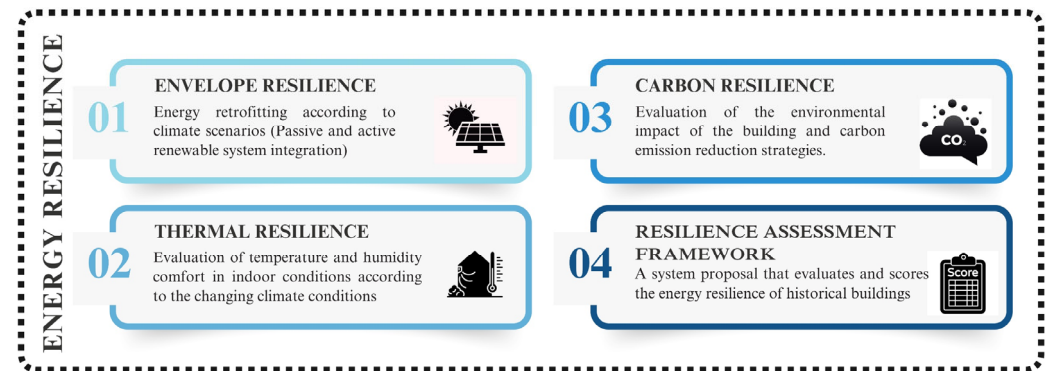


Figure 5. Components affecting the energy resilience of historic buildings and evaluation approaches.

According to Figure 5, the concept of energy resilience has been classified into four subheadings based on studies in the literature. These classifications address aspects that can enhance the resilience of historic buildings in various contexts. Thermal resilience can be defined as the ability of a building to maintain appropriate indoor comfort levels under conditions such as extreme temperature, humidity, or sudden climate changes without excessive reliance on mechanical systems. Building envelope resilience is the ability of a building's exterior surfaces, including walls, roofs, windows, and foundations, to maintain their performance in terms of energy against climate-related risks such as humidity and wind. Carbon resilience is the ability of a building to reduce, adapt, and manage its carbon footprint throughout its lifespan, both during operation and renovation. The final heading, "Resilience Assessment Framework," refers to a holistic resilience and scoring system that incorporates multiple parameters.

3.3. Sociocultural Resilience

The significance of cultural heritage in ensuring the sustainability and resilience of human settlements is recognized in the international record. Cultural heritage represents the tangible and intangible values of a society's identity, which constitutes an important component of people's satisfaction and belonging. Society's recognition of cultural heritage's social, cultural, environmental, and economic "resource" value is a progressive step towards improving quality of life, strengthening economic growth, and improving social communication [69]. International documents and records contributing to the 2030 Agenda for Sustainable Development emphasize the value of cultural heritage for the region's and communities' resilience. The Hangzhou Declaration, which is the outcome document of the UNESCO International Congress in May 2023, with the support of the Government of the People's Republic of China, emphasizes putting culture at the centre of the policies developed in the sustainable growth process and ensuring cultural resilience. This declaration states that the appropriate protection of the heritage, including cultural landscapes, and the preservation of relevant traditional knowledge, values, and practices in synergy with other scientific knowledge will enhance the resilience of communities to disasters and climate change. Through cultural activities and restoring their cultural legacy and institutions, disaster-affected individuals and communities must regain and improve their feeling of normalcy, self-worth, sense of place, and confidence in the future [37]. The Framework Convention on the Value of Cultural Heritage for Society, established by the

Council of Europe, is another significant international agreement [70]. This agreement refers to the active role of people in recognizing, preserving, and transmitting cultural heritage and its values to future generations. The agreement also addresses the relevance of “Heritage Community Resilience”. It presents a conceptual framework that addresses a process whereby cultural heritage supports building a society that can prevent, deal with, and recover from the adverse impacts to which it is exposed. Making cities and settlements accessible, safe, sustainable, and resilient while highlighting the importance of cultural heritage is one of the most crucial components of the United Nations Agenda 2030 and the new international policy for Disaster Risk Reduction 2015–2030 [45].

The significance of maintaining cultural diversity and promoting cultural pluralism in developing sociocultural resilience is recognized in strengthening identity and a sense of place when disasters occur. In addition, cultural heritage provides important capacities for adapting conventional knowledge and abilities to contemporary environmental and social circumstances by providing evidence of the traces of past societies and environmental changes [71]. Settlements today face global and local challenges such as climate change, globalization, drought, human migration, ageing populations, and economic and social challenges. In tackling these challenges, there is an absence of funding for upkeep and rehabilitation, and a lack of knowledge and skills to preserve the sociocultural resilience of cultural heritage. Consequently, in improving the resilience of the built environment and cultural heritage sites, it is significant to adopt strategies that aim to protect and enhance cultural heritage and include community participation to improve quality of life. Cultural heritage sites will significantly contribute to resilience studies by providing a process and an effective tool that enhances people’s capacity and communities to decide and turn those judgments into action, from information to planning, implementation, and monitoring [69].

3.4. Economic Resilience

The increasing effect of climate change and challenges, urbanization, and population growth are causing significant societal problems. Due to climate change-induced effects, these problems result in massive and threatening impacts on local and global economies [72]. The IPCC emphasizes the relative sensitivity of various geographies to the challenges of climate change, particularly in developing countries and coastal areas. Economic challenges are increased by various risks, such as inundation, coastal flooding, coastal erosion, and drought response, which add additional burdens to today’s economic development concerns. In this context, communities are called upon to raise awareness through calls to improve local capability for both infrastructure and economic sustainability [73,74]. However, the climate change mitigation strategies proposed by these calls have high economic inputs that are difficult to meet in developing countries. However, cultural heritage sites may become unusable over time if societies do not allocate the necessary budgets to combat climate change. Therefore, the local economy can be damaged due to climate-induced disruptions [72].

Climate change continues to affect countries’ economies, social welfare, ecosystems on land and in water, and the organization of their geopolitical, political, and institutional spaces. Climate change has far-reaching consequences for cities, coastal areas, and landscapes, especially economically. In the scale of cities, climate change is a factor that disrupts and changes projects by causing energy supply disruptions, infrastructure risks, and food and drinking water shortages. All these changes affect financial policies and recovery strategies as they lead to monetary reduction and capital reconstruction [75]. In this context, resources should be used more efficiently through risk-based prioritization and analysis, sustainable materials and techniques should be used, community-based protection should be ensured, and low-budget, effective solutions should be pursued.

As a result of the four resilience topics examined within the scope of the study, a comprehensive literature review was conducted on the concept of “energy resilience”, which constitutes the focus of the study. In this context, data was collected from the literature on the necessary components, development strategies, and how AI-based prediction and evaluation tools can be integrated into this process.

4. Methodology

Extreme climatic events, social transformation, economic resource constraints, and changes in energy demands make preserving historic buildings a more complex and multi-dimensional issue. This study addresses four main resilience areas (climate-based disaster resilience, sociocultural resilience, economic resilience, and energy resilience) to increase historic buildings’ resilience against changing climatic conditions. Each scope explains the resilience mechanisms necessary for the sustainable conservation of historic buildings. Furthermore, the study deepens the topic of energy resilience. It is analyzed under four subheadings: building envelope resilience, resilience in carbon emission reduction, thermal resilience, and holistic resilience development frameworks. This methodological approach aims to contribute to understanding the resilience capacities of historic buildings against climate change and to developing new conservation strategies specific to energy resilience with an AI-based approach.

The study’s methodology consists of four phases structured within a qualitative research framework to address the identified problem and achieve the objective. The study involves (1) systematically scanning literature from international databases, (2) identifying research trends related to energy resilience through content analysis, (3) identifying AI integration and potential within the framework based on identified gaps in the literature, and (4) developing a conceptual framework based on this data, including an AI-assisted assessment and prediction for historic buildings (Figure 6).

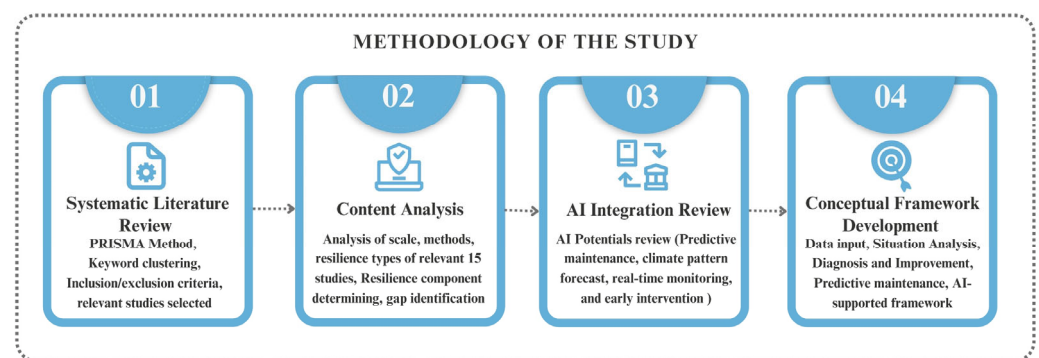


Figure 6. The study’s four-stage methodological approach.

4.1. Systematic Literature Review with PRISMA Guidance

This study created three keyword groups to reach the targeted studies. These phrases are “cultural heritage” or “tangible cultural heritage,” or “historic building” or “historic building”(Topic) AND “thermal resilience” or “energy resilience,” or “envelope resilience” or “carbon resilience” or “resilience assessment” or “resilience score” or “reducing greenhouse gas” (Topic) AND “climate change” (Topic) and were searched in Web of Science and Scopus databases. In the search, 94 sources, such as year range, type of publication, or publication language, were found without restriction. The sources accessed in the study were screened according to the four-stage process using the PRISMA method [76] and analyzed according to availability and coverage. According to the analysis, 15 studies that formed the focus of the study and covered all three keyword groups were found (Figure 7).

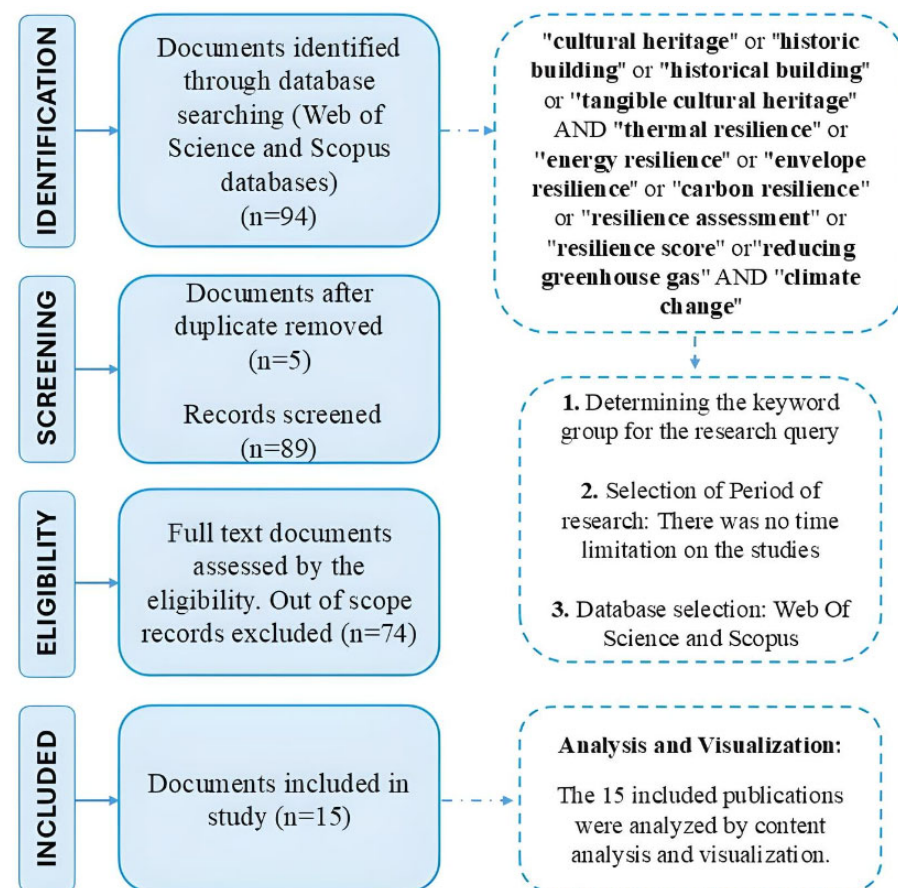


Figure 7. The selection process of articles uses the PRISMA method.

4.2. Content Analysis

Within the scope of the study, 15 academic publications containing all three keyword groups and focusing on energy resilience were examined, and a comprehensive content analysis was conducted in this direction. The selection of these 15 publications was based on their relevance to the topic. Studies that addressed the topic solely within the context of historical buildings and energy but did not address climate change or future risk resilience were excluded. These studies were analyzed in terms of implementation scale, field study, building type, resilience approach, study method, purpose, findings, and conclusions. This way, a comparative analysis of the existing literature's trends, methodological differences, and focus was conducted to determine research gaps, challenges, and upcoming studies' needs in this area (Table 2).

In this study, the publications included in the content analysis were classified under certain groups in line with their similarities and differences. While some of the analyzed studies conducted their analyses at the building scale, others dealt with the context of historic districts or the urban level. In studies conducted at the urban scale, the heat island effect is generally considered within the scope of the resilience approach; adaptation strategies are developed for microclimate conditions, and thermal comfort analyses are intensively carried out in this direction. As the scale of the research decreases, the degree of detail of the methods used in the analyses increases, and various scenarios are produced through simulations based on climate data covering near periods, such as 2020–2050, and distant periods, such as 2050–2100. Through these scenarios, the heating–cooling loads of the buildings are calculated, and thermal comfort conditions are assessed to address multiple resilience strategies (e.g., building envelope improvements and thermal comfort optimization). However, some studies focus only on indoor air quality, while others directly

assess the performance of the building envelope. When the methodological approaches used are analyzed, it is seen that the simulation method is the most frequently used method with future weather data on climate change. In addition, field measurements and monitoring with various sensors are also included in the data collection process.

Table 2. Content analysis of the 15 academic publications analysed.

Reference	Scale	Case Study	Resilience Approach	Method	Aim	Findings and Conclusions
[15]	Urban	Scenario based on the Canadian climate	Building Envelope and Thermal Resilience	Simulation, Thermal and hygrothermal measurements)	Determines how climate change affects the performance and resilience of building envelopes.	With its adaptive design to different climatic conditions, the study can be a tool for performance prediction in the upcoming climate change.
[77]	Building	Barcelona residential buildings	Thermal Resilience	Simulation	Analyzes how the behaviour of buildings will change in scenarios where extreme temperatures are predicted to increase in summer.	Shows that overheating reduces thermal endurance in ventilation scenarios and affects the comfort of the air conditioner.
[16]	Building	Le Corbusier's modern architecture buildings	Building Envelope and Thermal Resilience	Simulation	Develops energy and indoor environmental quality solutions by analyzing Le Corbusier's studio apartment.	Adaptive strategies were found to be important in increasing resilience in buildings against climatic conditions.
[78]	Urban	Gubbio/Italy Palazzo dei Consoli	Thermal Resilience (indoor and outdoor)	Field Monitoring and Simulation	Provides an approach for heritage sites by combining field monitoring and numerical modelling.	It reveals that the proposed analysis helps understand the impact of cultural heritage on indoor and outdoor spaces.
[28]	Urban	Molfetta Historical District/Italy	Envelope Resilience	Data collection and the Geographical clustering method	Analyzes and quantify process hazards and plan strategic actions to reduce hazards.	The management system in the study's strategy seems helpful in defining actions and analysing each case study.
[29]	Urban	Athens Historical Centre/Greece	Thermal Resilience	Thermal Sensation-Ginovi method, Discomfort Index	Develops a plan for how users can adapt to adverse thermal conditions.	Develops a feasible climate change resilience plan to assess the impacts of urban warming.
[79]	Urban	92 structures in Florianopolis, Brazil	Thermal Resilience	Simulation and resilience assessment method	Evaluates the thermal resilience of heritage to assess the risk of indoor overheating.	Reveals the necessity of strategies developed for adaptive design in resilience planning.
[80]	Building	Review of various buildings in New Zealand	Building Envelope and Thermal Resilience	Examining strategies through qualitative research	Assesses energy and seismic resilience through current policies and practices.	Emphasizes the importance of integrated approaches to energy and seismic retrofitting.
[81]	Urban	Open spaces in Campi, Venice	Thermal Resilience (outdoor)	Simulation and Physiological Equivalent Analysis	Provides improvements to enhance the thermal comfort of urban areas.	Contributes to assessing and strengthening heritage based on climate change.
[41]	Building	Casa dell'Angelo/Italy	Thermal Resilience (indoor)	On-site monitoring and Simulation	Proposes responsive renovation strategies to increase the resilience of historic buildings.	Shows that microclimate-controlled air conditioning systems reduce energy consumption.

Table 2. Cont.

Reference	Scale	Case Study	Resilience Approach	Method	Aim	Findings and Conclusions
[82]	Urban	Historic residences in the Cádiz region	Building Envelope Resilience	Monitoring and data collection in the field (data logger, sensors)	Examines bioclimatic design approaches and how the city will adjust to changing climate conditions.	Shows that historic dwellings are climate-adapted and have potential for improvement.
[83]	Urban	Mediterranean region/Italy	Building Envelope Resilience	Simulation and in situ measurement	Develops an approach that includes energy retrofitting, transformations, and conservation.	Investigates the role of compactness, light-colored materials, and roofs against microclimate changes.
[84]	Building	United Kingdom/China (industrial buildings)	Carbon Resilience	Quantitative review through Life Cycle Analysis	Advocates for the need and guidelines for including embodied carbon.	Shows the contribution of the inclusion of embodied carbon to potential carbon savings.
[85]	Building	Vancouver, Ottawa, Charlot-tetown/Canada	Thermal Resilience	Simulation and resilience measurements	Provides practitioners with an assessment framework for building resilience.	Contributes to developing building codes for climate change-compatible infrastructures.
[67]	Building	A review of studies in the literature	Building Envelope Resilience	Analysis of strategies based on hydrophilic characteristics	Assesses the moisture compatibility of façade renovation and insulation materials.	Emphasizes the importance of moisture compatibility of thermal insulation materials in façade renovation.

Regarding the research questions, most studies center on historical buildings, climate change, and thermal comfort. Only one of the studies analyzed in the content analysis included a carbon emission reduction target. This study [84], which addresses carbon resilience in the context of climate change, contributes to a significant gap in the literature by using an LCA approach. Studies on carbon at the intersection of historic buildings, energy resilience, and climate change are limited. Furthermore, conducting LCA analyses and assessing the carbon emissions of historic buildings, which constitute a significant share of the building stock, aligns with the goals of the Paris Agreement and would make a significant contribution. Studies in this area should be increased, focusing on results and proposing solutions in the context of the climate crisis. The distribution of the 15 studies analyzed according to various criteria is shown in Figure 8 on the Sankey diagram.

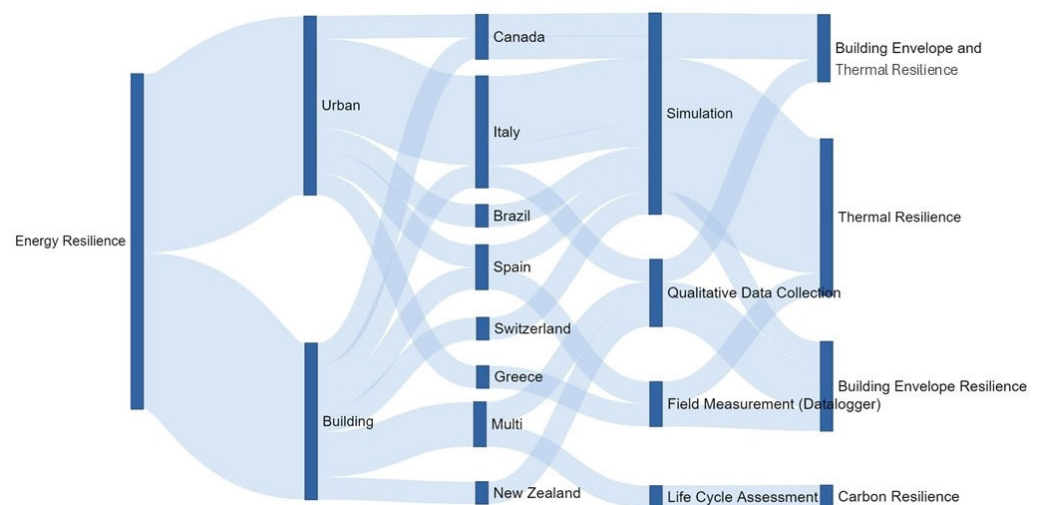


Figure 8. Distribution of the studies that were content analyzed through the Sankey diagram.

4.3. AI Integration Review and Potentials

The third phase of the study's methodology focuses on examining AI integration and identifying its potential. The literature presents applications of AI in the context of historic buildings and their preservation. However, its use in the context of climate change and energy resilience, its use in identifying future risks, and its development in climate adaptation and resilience have been identified as lacking. Furthermore, the need for measurement and evaluation tools to enhance the energy resilience of historic buildings [86] highlights the importance and novelty of AI integration. In this context, the use of AI in literature was examined, identifying the potential for integrating AI technologies into the conceptual foundations of building envelopes, thermal comfort, and carbon emission reduction. Both theoretical and applied studies were evaluated, considering application areas such as AI-supported energy modeling, digital twins, thermal behavior patterns, risk assessment, and decision support systems. The key components and integration methods through which AI technologies can contribute to energy resilience were systematically analyzed in this context.

AI technologies have been included in the conceptual framework because of their applicability and potential in the context of climate change and energy resilience. AI is important in predictive forecasting and decision systems with machine learning (ML) and artificial neural networks (ANN), where researchers analyze multiple and complex data sets. ML can develop algorithms to learn from data and make predictions based on data sets. These technologies can suggest climate models by processing data on issues such as precipitation trends, temperature records, and sea level rise, to determine the environmental effects of the structure on a yearly basis from climate data in terms of pattern creation. ML also has the potential to automate the detection of extreme weather events or long-term climatic changes and the identification of anomalies [87]. In addition, AI algorithms can significantly contribute to making optimal decisions and mitigating climate strategies in carbon capture technologies and renewable energy integration. As climate data becomes increasingly complex, AI technologies will play a critical role in understanding this complexity and developing patterns. AI's contributions to extreme weather forecasting and early response systems by processing real-time data will be significant in its integration with energy resilience and historical studies.

While AI offers significant opportunities in energy resilience, its application, particularly in the context of historic buildings, presents limitations and challenges. One of the most fundamental challenges is data quality and availability: many historic buildings' digital documentation contains incomplete, inconsistent, or machine-unreadable data. Issues of quality and accessibility, standardization, and inter-program transferability of data, such as environmental monitoring, thermal values of material properties, or restoration documentation, are common in historic buildings. Such buildings often lack a continuous sensor network or digitized data, making it challenging to train reliable AI models. Furthermore, integrating high-resolution simulations with real-time data streams and predictive modeling within the same framework can pose computational challenges, particularly in resource-limited conservation contexts. These challenges highlight the need for adaptable and scalable AI approaches incorporating hybrid modeling strategies capable of working with fragmented or low-resolution data for cultural heritage applications. By addressing these issues, AI's potential could significantly contribute to historic buildings' conservation and energy resilience.

In this context, developing an AI-supported assessment and prediction framework requires specific inputs and data. These datasets require defined input variables (e.g., building type, climate zone, material data, etc.), datasets for supervised learning and scenario generation, ML-based training of the datasets to the system, regression models

for resilience performance assessment and indicators, supervised classification models for vulnerability assessment, and interpretability mechanisms and natural language processing (NLP) processes for the decision support system. Specific data requirements must be met in four key layers (Data Collection, Performance Analysis, Improving and Predictive Modeling, and AI-Assisted Decision Support Systems) to implement the proposed AI-supported framework. During the data collection phase, devices capable of simultaneously capturing data with smart temperature and humidity sensors are required to monitor indoor comfort and envelope behaviour. Data on historical building materials (e.g., thermal conductivity, U-value, and moisture behaviour) is limited, especially in historical buildings, and is often not digital. Therefore, field-collected data for calibration will be compared with simulations using thermal cameras, data loggers, and U-value measurement devices. Environmental climate-based data sources should include regionalized high-resolution climate projections based on Shared Socioeconomic Pathways (SSP) scenarios, preferably CMIP6 or CORDEX. Optimal decisions derived from remediation scenarios and patterns learned through ML will form the data for predictive modeling and decision support systems. However, existing historical building inventories often have non-standard digital formats, posing challenges for training AI models. These limitations lead us to develop a framework that includes hybrid modeling approaches that can work with fragmented and analog data, especially in data-scarce contexts.

In this process, a theoretical, practical, data-driven, and technology-based framework has been structured, considering the optimization potentials of energy performance prediction and scenario-based decision support systems with machine-learning algorithms in determining buildings vulnerable to climate change (Figure 9).

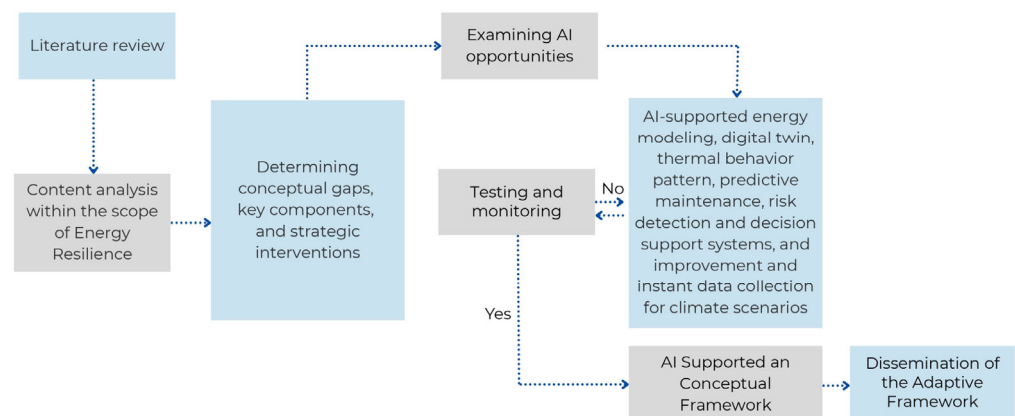


Figure 9. AI-supported conceptual framework development stages and flow.

The integration of artificial intelligence algorithms based on supervised learning is recommended to validate the predictive dimension of the developed framework. Models such as artificial neural networks, random forest regression, and support vector machines will be used. These algorithms will be trained on hybrid datasets combining building sensor data (e.g., temperature, humidity) and simulation outputs (e.g., heat load, envelope deterioration). The aim is to estimate thermal resilience, shell resilience loss, and retrofit requirements under different SSP climate scenarios. Normalization and missing data completion methods will be applied in the data preprocessing stages. Model validation is proposed using k-fold cross-validation and scenario-based stress testing. The output generated will be integrated into AI-based decision support modules for early intervention mechanisms and resilience-building scenarios. These methods will enable the framework to move from conceptual to technically feasible.

4.4. Developed Conceptual Framework and Discussion

The final phase of the study's methodology, the development of the conceptual framework, is based on data obtained in the first three phases. The first phase identified gaps in the literature, the second phase identified the energy resilience components and methodological deficiencies, and the third phase identified the qualities and potential of the AI tool to be developed. In the final phase, this data was synthesized, and a conceptual framework based on literature findings was proposed to enhance the energy resilience and adaptive capacity of historical buildings in the face of climate change. This conceptual framework, intended to guide future studies focused on energy resilience, encompasses the following topics: building envelopes, thermal retrofitting, life cycle analysis, carbon emission reduction targets, integration of technological systems, adaptation to climate change, integration with socioeconomic policies, and the development of a disseminated system for cultural heritage by international standards. The framework developed in this regard has four stages: situation analysis, improvement scenarios, adaptive system integration and monitoring, and dissemination activities (Figure 10).

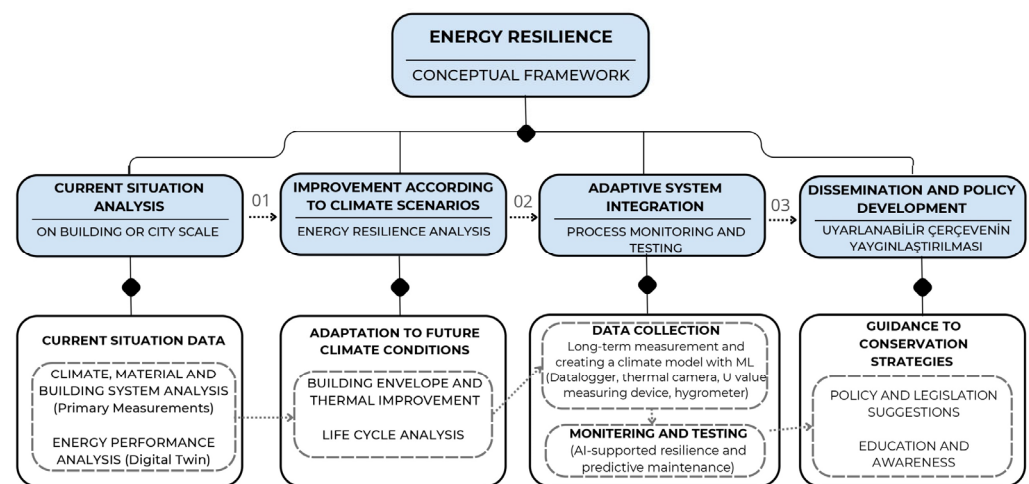


Figure 10. The energy resilience framework is proposed in the study.

A methodological approach has been developed by integrating the conceptual framework and AI-enabled tools and technologies at various stages. Each framework component serves as an input layer in the AI-powered decision-making system and optimization of scenario-driven improvements. In the first process, it is recommended to analyze the status of the building, determine its current performance with artificial intelligence-supported simulation tools, and create its digital twin. The second phase of the conceptual framework, future scenarios (based on IPCC's SSP), is anticipated to significantly contribute to forming climate patterns and AI-based climate pattern creation and prediction. In this way, it is possible to evaluate the current situation and predict how the performance of the building will change under different climate scenarios; thus, intervention decisions can become more accurate and effective. It is expected that the third phase, integrating the collected primary data into the AI-based system and its monitoring and testing, will provide significant contributions to the resilience of the historical building through predictive maintenance and early intervention opportunities. The final stage, real-time monitoring, will ensure that strategies validated and tested through predictive analysis are disseminated to make informed decisions and preserve historical buildings for future generations. By integrating decision support systems in AI-based structured data analysis, the framework gains importance as a tool that balances conservation with energy resilience. In this respect, the framework highlights the transformative potential of AI technologies that offer adaptable and interactive solutions by proposing data-driven strategies for the resilience of historical

buildings to climate risks. It will also enable conservationists and policy makers to set priorities, monitor progress, and make informed decisions that facilitate the transition to lower-carbon and more resilient historical buildings.

To illustrate how the proposed framework can be applied in practice, consider a functional building constructed of historically valuable masonry, stone, or wood located in a humid climate zone (e.g., Southern China or Asia). For this building, which experiences thermal comfort problems and deterioration in the building envelope during the summer months, data such as temperature, humidity, and surface condition will be collected on-site using smart sensors and historical climate records. Subsequently, AI-supported energy simulations (e.g., EnergyPlus, Design Builder) will be implemented based on SSP-based scenarios for 2050. Based on the resulting performance predictions (ML), AI-supported decision tools will recommend the most appropriate retrofit strategies (dynamic shading, moisture control layers, or low-carbon insulation materials). This scenario demonstrates how the layered structure of the proposed framework (data, diagnostics, retrofitting, prediction, decision support) can be integrated into the energy resilience development process of historical buildings against future climate pressures. Optimized decisions will be disseminated, providing an adaptable basis for historical buildings with similar climates and techniques.

5. Conclusions and Recommendations for Future Work

Climate change and its effects are among the most critical challenges worldwide. Climate change's effects are multifaceted and becoming more detrimental to nature and human existence. Today's conservation and environmental policies must adopt a multi-disciplinary strategy to sustain historic buildings. In this context, developing strategies for cultural heritage to adjust to climate change and make it more resilient comes to the fore. In this context, the concept of energy resilience concentrates on the ability of buildings to maintain their function and quality and not compromise on energy losses according to changing climatic and environmental conditions. It also includes the development of approaches specific to historical buildings in this regard. It is also the entire process of developing energy resilience, providing appropriate solutions without damaging the cultural values of the building, developing passive air conditioning facilities, and, where necessary, active system integration according to legal rules. It is seen that this concept, which is important for historical buildings, has only recently been mentioned in literature.

This study emphasizes the significance of energy-oriented approaches in ensuring historical buildings' sustainability and adapting to future climate conditions. It also proposes an AI-based conceptual framework for energy resilience. The framework proposed in this study aims to preserve and optimize historic buildings' physical energy performance. The conceptual framework presents a holistic approach, from analyzing the current state of historic buildings to improving strategies (in the building envelope and thermal comfort) to monitoring and evaluation mechanisms for preparedness for future conditions. It also emphasizes integrating cultural sustainability with ecological and innovative systems, focusing on analyzing the carbon emissions caused by the historical building in its life cycle. Within the scope of AI integration into the conceptual framework, it is suggested to define decision support systems for energy consumption, detection of fragile building components, and early intervention with predicted models of the performance of the building in the coming years under different climate scenarios. In this way, it is aimed to benefit from the decision-making equipment of the proposed framework with data-based prediction and predictive maintenance. Thus, historical buildings, which have become vulnerable to today's climate conditions, are expected to be more resilient and sustainable in terms of energy and contribute to social, economic, and cultural policies. Integrating all these

processes in line with international standards requires a theoretical and methodological approach applicable to all world heritage.

As a result, in tackling the climate crisis in historic buildings, issues such as energy sustainability and environmental impacts should also be considered, instead of only a conservation-oriented approach. This conceptual framework, developed in this direction, provides an AI-based tool for conservation and climate adaptation policies by providing a holistic and data-driven perspective on energy resilience and forms the basis for application for future research. This study highlights the gaps in existing literature (carbon reduction target in historic buildings and holistic approach including LCA) by presenting an approach to increase energy resilience. This energy resilience conceptual framework, which aims to minimize historical buildings' environmental impacts and energy consumption throughout their life cycle, offers a holistic approach to increasing adaptation to climate change and reshaping conservation policies accordingly.

In future studies, testing the applicability of this framework in different geographical and cultural contexts with field applications in various climatic zones and simulation of future weather data will contribute theoretically and practically to the literature on the subject. To test, validate, and assess the transferability of the proposed framework, future research will conduct empirical applications on selected historical buildings located in different climatic zones and geographical regions. Case study areas will be selected considering (i) climatic stress profile (e.g., temperature range, humidity index, precipitation variability), (ii) typological and material properties (e.g., masonry, timber, hybrid systems), and (iii) policy and regulatory framework (e.g., conservation legislation, energy efficiency codes). During the implementation phase, methods such as real-time data monitoring with environmental sensors, heating and cooling load simulation analyses, simulation-based predictions under SSP scenarios, and AI-assisted performance modeling (ML models for energy demand, degradation mapping, adaptive retrofit recommendations) will be employed. These multi-context applications will provide quantitative data-driven assessments of the scalability, sensitivity, and practical utility of the framework. Also, a multi-stage validation plan is proposed for future research, including (i) pilot testing with field data on selected historical buildings under different climatic conditions, (ii) comparison of model outputs with traditional simulation tools, and (iii) expert reviews using the Delphi method to assess the quality of the decision support system and the AI-based framework. The model's predictive performance, adaptability to low-data environments, and integration with decision support systems will be evaluated. These analyses will demonstrate the AI-based framework's contribution, accuracy, and scalability in the context of cultural heritage climate resilience. Furthermore, for future studies, elaborating this conceptual framework and developing a method that will enable the quantitative analysis of the energy resilience of historic buildings by assigning weight coefficients to each component will make a significant contribution to addressing a gap in the literature that has been discussed for modern buildings but has not been sufficiently studied in historic buildings.

Author Contributions: Conceptualization, B.Ö. and S.A.S.; methodology, B.Ö.; software, B.Ö.; validation, B.Ö., S.A.S. and Y.A.; formal analysis, S.A.S. and Y.A.; investigation, B.Ö.; resources, B.Ö. and S.A.S.; data curation, B.Ö., S.A.S. and Y.A.; writing—original draft preparation, B.Ö.; writing—review and editing, B.Ö. and S.A.S.; visualization, B.Ö.; supervision, S.A.S. and Y.A.; project administration, S.A.S. and Y.A. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The raw data supporting the conclusions of this article will be made available by the authors on request.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

SSP	Shared Socioeconomic Pathway
LCA	Life Cycle Assessment
SDGs	Sustainable Development Goals
AI	Artificial Intelligence
ML	Machine Learning
ANN	Artificial Neural Network
NLP	Natural Language Processing
IPCC	Intergovernmental Panel on Climate Change
HVAC	Heating, Ventilation, and Air Conditioning

References

1. IPCC. *IPCC, Climate Change 2022: Impacts, Adaptation and Vulnerability*; C.U. Press: New York, NY, USA; Available online: <https://www.ipcc.ch/report/ar6/wg2/> (accessed on 8 July 2025).
2. Mitchell, D.; Heaviside, C.; Vardoulakis, S.; Huntingford, C.; Masato, G.; Guillod, B.P.; Frumhoff, P.; Bowery, A.; Wallom, D.; Allen, M. Attributing human mortality during extreme heat waves to anthropogenic climate change. *Environ. Res. Lett.* **2016**, *11*, 074006. [CrossRef]
3. IPCC. *IPCC, AR5 Climate Change 2014: Impacts, Adaptation, and Vulnerability*. Available online: <https://www.ipcc.ch/report/ar5/wg2/> (accessed on 9 July 2025).
4. Nicholls, R.J.; Brown, S.; Goodwin, P.; Wahl, T.; Lowe, J.; Solan, M.; Godbold, J.A.; Haigh, I.D.; Lincke, D.; Hinkel, J.; et al. Stabilization of global temperature at 1.5 °C and 2.0 °C: Implications for coastal areas. *Philos. Trans. R. Soc. A Math. Phys. Eng. Sci.* **2018**, *376*, 20160448. [CrossRef] [PubMed]
5. IEA. *Perspectives for the Clean Energy Transition—Analysis—IEA 2019*. Available online: <https://www.iea.org/reports/the-critical-role-of-buildings> (accessed on 3 July 2025).
6. Maduta, C.; Melica, G.; D’Agostino, D.; Bertoldi, P. Towards a decarbonised building stock by 2050: The meaning and the role of zero emission buildings (ZEBs) in Europe. *Energy Strategy Rev.* **2022**, *44*, 101009. [CrossRef]
7. European Commission. *European Commission: The European Green Deal*. 2019. Available online: https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal_en (accessed on 3 July 2025).
8. ICOMOSS. *The Future of Our Pasts: Engaging Cultural Heritage in Climate Action*. Outline of Climate Change and Cultural Heritage. Available online: https://publ.icomos.org/publicomos/jlbSai?html=Bur&base=technica&ref=43205&file=1885.pdf&path=CCHWG_final_print.pdf (accessed on 16 June 2025).
9. Markham, A.; Osipova, E.; Samuels, K.L.; Caldas, A. *World Heritage and Tourism in a Changing Climate*; UNESCO Publishing: Paris, France, 2016.
10. Gagnon, A.S.; Sesana, E.; Bertolin, C.; Loli, A.; Hughes, J.; Leissner, J. Increasing the Resilience of Cultural Heritage to Climate Change Through the Application of a Learning Strategy. In *Proceedings of the Transdisciplinary Multispectral Modeling and Cooperation for the Preservation of Cultural Heritage*, Athens, Greece, 10–13 October 2018.
11. Fatorić, S.; Seekamp, E. Are cultural heritage and resources threatened by climate change? A systematic literature review. *Clim. Change* **2017**, *142*, 227–254. [CrossRef]
12. Dastgerdi, A.S.; Sargolini, M.; Pierantoni, I. Climate change challenges existing cultural heritage policy. *Sustainability* **2019**, *11*, 5227. [CrossRef]
13. Cacciotti, R.; Kaiser, A.; Sardella, A.; De Nuntiis, P.; Drdácý, M.; Hanus, C.; Bonazza, A. Climate change-induced disasters and cultural heritage: Optimizing management strategies in Central Europe. *Clim. Risk Manag.* **2021**, *32*, 100301. [CrossRef]
14. Santangelo, A.; Melandri, E.; Marzani, G.; Tondelli, S.; Ugolini, A. Enhancing resilience of cultural heritage in historical areas: A collection of good practices. *Sustainability* **2022**, *14*, 5171. [CrossRef]
15. Soudian, S.; Berardi, U. Impact of future climate scenarios on thermal performance and resilience of building façades: Canadian climate case study. *Build. Environ.* **2025**, *267*, 112245. [CrossRef]
16. Lamberti, G.; Contrada, F.; Kindinis, A. Exploring adaptive strategies to cope with climate change: The case study of Le Corbusier’s Modern Architecture retrofitting. *Energy Build.* **2024**, *302*, 113756. [CrossRef]

17. Angeles, K.; Patsialis, D.; Taflanidis, A.A.; Kijewski-Correa, T.L.; Buccellato, A.; Vardeman, C. Advancing the design of resilient and sustainable buildings: An integrated life-cycle analysis. *J. Struct. Eng.* **2021**, *147*, 04020341. [CrossRef]
18. Angrisano, M.; Fabbrocino, F.; Iodice, P.; Girard, L.F. The evaluation of historic building energy retrofit projects through the life cycle assessment. *Appl. Sci.* **2021**, *11*, 7145. [CrossRef]
19. Obead, R.; Khaddour, L.; D'Amico, B. Historical Building Energy Retrofit Focusing on the Whole Life Cycle Assessment—A Systematic Literature Review. *Architecture* **2025**, *5*, 49. [CrossRef]
20. Fiorini, L.; Conti, A.; Pellis, E.; Bonora, V.; Masiero, A.; Tucci, G. Machine Learning-Based Monitoring for Planning Climate-Resilient Conservation of Built Heritage. *Drones* **2024**, *8*, 249. [CrossRef]
21. Bakirman, T.; Kulavuz, B.; Bayram, B. Use of Artificial Intelligence Toward Climate-Neutral Cultural Heritage. *Photogramm. Eng. Remote Sens.* **2023**, *89*, 163–171. [CrossRef]
22. Torkamani, M.H.; Shahbazi, Y.; Oskoyi, A.b. Explaining resilience model of historical bazaars using artificial neural network. *Smart Sustain. Built Environ.* **2024**, *13*, 1538–1559. [CrossRef]
23. Rahaman, Z.A.; Kafy, A.A.; Fattah, M.A.; Saha, M. Enhancing Urban Ecological Risk Assessment by Integrating Spatial Modeling and Machine Learning for Resilient Environmental Management in UNESCO World Heritage Cities. *Earth Syst. Environ.* **2024**, *13*, 1538–1559. [CrossRef]
24. Adetunji, O.S.; MacKee, J. Frameworks for climate risk management (CRM) in cultural heritage: A systematic review of the state of the art. *J. Cult. Herit. Manag. Sustain. Dev.* **2023**. [CrossRef]
25. Orr, S.A.; Richards, J.; Fatorić, S. Climate change and cultural heritage: A systematic literature review (2016–2020). *Hist. Environ. Policy Pract.* **2021**, *12*, 434–477. [CrossRef]
26. Aktürk, G.; Dastgerdi, A.S. Cultural landscapes under the threat of climate change: A systematic study of barriers to resilience. *Sustainability* **2021**, *13*, 9974. [CrossRef]
27. Crowley, K.; Jackson, R.; O'connell, S.; Karunarthna, D.; Anantasari, E.; Retnowati, A.; Niemand, D. Cultural heritage and risk assessments: Gaps, challenges, and future research directions for the inclusion of heritage within climate change adaptation and disaster management. *Clim. Resil. Sustain.* **2022**, *1*, e45. [CrossRef]
28. Elena, C.; Fabio, F. Energy resilience of historical urban districts: A state of art review towards a new approach. *Energy Procedia* **2017**, *111*, 426–434. [CrossRef]
29. Santamouris, M.; Cartalis, C.; Synnefa, A. Local urban warming, possible impacts and a resilience plan to climate change for the historical center of Athens, Greece. *Sustain. Cities Soc.* **2015**, *19*, 281–291. [CrossRef]
30. Mann, M.E.; Bradley, R.S.; Hughes, M.K. Northern hemisphere temperatures during the past millennium: Inferences, uncertainties, and limitations. *Geophys. Res. Lett.* **1999**, *26*, 759–762. [CrossRef]
31. Grove, J.M. *Little Ice Ages: Ancient And Modern*; Taylor & Francis: Oxfordshire, UK, 2004; Volume 1.
32. IPCC. Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. IPCC. Available online: <https://www.ipcc.ch/report/ar6/syr/> (accessed on 4 July 2025).
33. UNFCCC. What is the United Nations Framework Convention on Climate Change? | UNFCCC. 1992. Available online: <https://unfccc.int/process-and-meetings/what-is-the-united-nations-framework-convention-on-climate-change> (accessed on 5 July 2025).
34. Sesana, E.; Gagnon, A.S.; Ciantelli, C.; Cassar, J.; Hughes, J.J. Climate change impacts on cultural heritage: A literature review. *Wiley Interdiscip. Rev. Clim. Change* **2021**, *12*, e710. [CrossRef]
35. O'Brien, G.; O'Keefe, P.; Jayawickrama, J.; Jigyasu, R. Developing a model for building resilience to climate risks for cultural heritage. *J. Cult. Herit. Manag. Sustain. Dev.* **2015**, *5*, 99–114. [CrossRef]
36. Gandini, A. Climate Change Risk Management for the Sustainable Development of the Historic City: From the Material to the Territory. Ph.D. Thesis, Universidad del Pais Vasco, Bilbao, Spain, 2017.
37. UNESCO. UNESCO World Heritage Centre. Case Studies on Climate Change and World Heritage. UNESCO World Heritage Centre. 2007. Available online: <https://whc.unesco.org/en/activities/473/> (accessed on 3 July 2025).
38. Troi, A. Historic buildings and city centres—The potential impact of conservation compatible energy refurbishment on climate protection and living conditions. In Proceedings of the International Conference Energy Management in Cultural Heritage, Dubrovnik, Croatia, 6–8 April 2011.
39. Economidou, M.; Atanasiu, B.; Despret, C.; Maio, J.; Nolte, I.; Rapf, O.; Laustsen, J.; Ruyssevelt, P.; Staniaszek, D.; Strong, D. *Europe's Buildings Under the Microscope. A Country-By-Country Review of the Energy Performance of Buildings*; Buildings Performance Institute Europe: Brussels, Belgium, 2011.
40. Karimpour, M.; Belusko, M.; Xing, K.; Boland, J.; Bruno, F. Impact of climate change on the design of energy efficient residential building envelopes. *Energy Build.* **2015**, *87*, 142–154. [CrossRef]
41. Cadelano, G.; Bortolin, G.; della Valle, A.; Ferrarini, A.; Cattaneo, G.; Peron, P.; Emmi, F. Thermal Behaviour of a Historic Building Housing Books Across Past and Future Climate Scenarios. *Heritage* **2025**, *7*, 6916–6937. [CrossRef]

42. Cho, H.M.; Yang, S.; Wi, S.; Chang, S.J.; Kim, S. Hygrothermal and energy retrofit planning of masonry façade historic building used as museum and office: A cultural properties case study. *Energy* **2020**, *201*, 117607. [CrossRef]
43. Historic England. Adapting Historic Buildings for Energy and Carbon Efficiency | Historic England. 2024. Available online: <https://historicengland.org.uk/images-books/publications/adapting-historic-buildings-energy-carbon-efficiency-advice-note-18/> (accessed on 20 July 2025).
44. Mouhcine, B. Architectural Resilience for Sustainable Development: A Bibliometric Analysis. *Sustain. Dev.* **2025**, *33*, 4976–5000. [CrossRef]
45. UNISDR. Making Cities Resilient' World Disaster Reduction Is Your City Ready? Information and Modalities for Nomination and Participation for Cities and Local Governments. 2010. Available online: www.unisdr.org/campaign (accessed on 3 July 2025).
46. IPCC. *Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*; Cambridge University Press: Cambridge, UK; New York, NY, USA, 2007.
47. Macalister, F. Preparing for the future: Mitigating disasters and building resilience in the cultural heritage sector. *J. Inst. Conserv.* **2015**, *38*, 115–129. [CrossRef]
48. Hu, H.; Qiao, X.; Yang, Y.; Zhang, L. Developing a resilience evaluation index for cultural heritage sites: Case study of Jiangwan Town in China. *Asia Pac. J. Tour. Res.* **2021**, *26*, 15–29. [CrossRef]
49. Downes, B.J.; Miller, F.; Barnett, J.; Glaister, A.; Ellemor, H. How do we know about resilience? An analysis of empirical research on resilience and implications for interdisciplinary praxis. *Environ. Res. Lett.* **2013**, *8*, 014041. [CrossRef]
50. Cannon, T.; Müller-Mahn, D. Vulnerability, resilience and development discourses in the context of climate change. *Nat. Hazards* **2010**, *55*, 621–635. [CrossRef]
51. Valagussa, A.; Frattini, P.; Crosta, G.; Spizzichino, D.; Leoni, G.; Margottini, C. Multi-risk analysis on European cultural and natural UNESCO heritage sites. *Nat. Hazards* **2021**, *105*, 2659–2676. [CrossRef]
52. Jentsch, M.F.; Bahaj, A.S.; James, P.A. Climate change future proofing of buildings—Generation and assessment of building simulation weather files. *Energy Build.* **2008**, *40*, 2148–2168. [CrossRef]
53. Blavier, C.L.S.; Huerto-Cardenas, H.E.; Aste, N.; Pero, C.D.; Leonforte, F.; Torre, S.D. Adaptive measures for preserving heritage buildings in the face of climate change: A review. *Build. Environ.* **2023**, *245*, 110832. [CrossRef]
54. Dore, M.H. Climate change and changes in global precipitation patterns: What do we know? *Environ. Int.* **2005**, *31*, 1167–1181. [CrossRef] [PubMed]
55. Han, Y.; Chun, Q.; Xu, X.; Teng, Q.; Dong, Y.; Lin, Y. Wind effects on Chinese traditional timber buildings in complex terrain: The case of Baoguo Temple. *J. Build. Eng.* **2022**, *59*, 105088. [CrossRef]
56. Sitzia, F.; Lisci, C.; Mirão, J. Accelerate ageing on building stone materials by simulating daily, seasonal thermo-hygrometric conditions and solar radiation of Csa Mediterranean climate. *Constr. Build. Mater.* **2021**, *266*, 121009. [CrossRef]
57. Gatto, A.; Drago, C. Measuring and modeling energy resilience. *Ecol. Econ.* **2020**, *172*, 106527. [CrossRef]
58. González, C.M.M.; Rodríguez, A.L.; Medina, R.S.; Jaramillo, J.R. Effects of future climate change on the preservation of artworks, thermal comfort and energy consumption in historic buildings. *Appl. Energy* **2020**, *276*, 115483. [CrossRef]
59. Magrini, A.; Franco, G. The energy performance improvement of historic buildings and their environmental sustainability assessment. *J. Cult. Herit.* **2016**, *21*, 834–841. [CrossRef]
60. Muñoz-González, C.M.; León-Rodríguez, A.L.; Campano-Laborda, M.; Teeling, C.; Baglioni, R. The assessment of environmental conditioning techniques and their energy performance in historic churches located in Mediterranean climate. *J. Cult. Herit.* **2018**, *34*, 74–82. [CrossRef]
61. Zhai, Z.J.; Helman, J.M. Implications of climate changes to building energy and design. *Sustain. Cities Soc.* **2019**, *44*, 511–519. [CrossRef]
62. Yang, Y.; Javanroodi, K.; Nik, V.M. Climate change and energy performance of European residential building stocks—A comprehensive impact assessment using climate big data from the coordinated regional climate downscaling experiment. *Appl. Energy* **2021**, *298*, 117246. [CrossRef]
63. Diaz-Lopez, C.; Verichev, K.; Holgado-Terriza, J.A.; Zamorano, M. Evolution of climate zones for building in Spain in the face of climate change. *Sustain. Cities Soc.* **2021**, *74*, 103223. [CrossRef]
64. Carreon, J.R. Review on Techniques, Tools and Best Practices for Energy Efficient Retrofitting on Heritage Buildings. REFOMO. Available online: https://refomo.eu/wp-content/uploads/sites/105/2015/11/Review-on-techniques-for-energy-efficient-retrofitting-of-heritage-buildings_Final.pdf (accessed on 23 June 2025).
65. Galatioto, A.; Ciulla, G.; Ricciu, R. An overview of energy retrofit actions' feasibility on Italian historical buildings. *Energy* **2017**, *137*, 991–1000. [CrossRef]
66. Cellura, M.; Ciulla, G.; Guarino, F.; Longo, S. Redesign of a rural building in a heritage site in Italy: Towards the net zero energy target. *Buildings* **2017**, *7*, 68. [CrossRef]
67. Posani, M.; Veiga, M.D.R.; de Freitas, V.P. Towards resilience and sustainability for historic buildings: A review of envelope retrofit possibilities and a discussion on hygric compatibility of thermal insulations. *Int. J. Archit. Herit.* **2021**, *15*, 807–823. [CrossRef]

68. Chan, K.T.; Chow, W.K. Energy impact of commercial-building envelopes in the sub-tropical climate. *Appl. Energy* **1998**, *60*, 21–39. [\[CrossRef\]](#)
69. Pinto, M.R.; Fabbriatti, K.; Bosone, M. Heritage Community Resilience for sustainable and resilient human settlements. In Proceedings of the XVII International Forum “Le Vie dei Mercanti”. World Heritage and Legacy, Naples, Italy, 8–9 June 2019; pp. 1120–1129.
70. Council of Europe. Council of Europe Framework Convention on the Value of Cultural Heritage for Society. 2005. Available online: <https://rm.coe.int/1680083746> (accessed on 3 July 2025).
71. Fatorić, S.; Egberts, L. Realising the potential of cultural heritage to achieve climate change actions in the Netherlands. *J. Environ. Manag.* **2020**, *274*, 111107. [\[CrossRef\]](#) [\[PubMed\]](#)
72. Hallegatte, S.; Green, C.; Nicholls, R.J.; Corfee-Morlot, J. Future flood losses in major coastal cities. *Nat. Clim. Change* **2013**, *3*, 802–806. [\[CrossRef\]](#)
73. Folke, C.; Carpenter, S.; Elmqvist, T.; Gunderson, L.; Holling, C.S.; Walker, B. Resilience and sustainable development: Building adaptive capacity in a world of transformations. *AMBIO A J. Hum. Environ.* **2002**, *31*, 437–440. [\[CrossRef\]](#) [\[PubMed\]](#)
74. Marsden, T.; Smith, E. Ecological entrepreneurship: Sustainable development in local communities through quality food production and local branding. *Geoforum* **2005**, *36*, 440–451. [\[CrossRef\]](#)
75. Allam, Z.; Jones, D. Climate change and economic resilience through urban and cultural heritage: The case of emerging small island developing states economies. *Economies* **2019**, *7*, 62. [\[CrossRef\]](#)
76. Page, M.J.; Moher, D.; Bossuyt, P.M.; Boutron, I.; Hoffmann, T.C.; Mulrow, C.D.; Shamseer, L.; Tetzlaff, J.M.; Akl, E.A.; Chou, R.; et al. PRISMA 2020 explanation and elaboration: Updated guidance and exemplars for reporting systematic reviews. *Res. Methods Rep.* **2021**, *372*, 1–36. [\[CrossRef\]](#)
77. Borghero, L.; Clères, E.; Péan, T.; Ortiz, J.; Salom, J. Comparing cooling strategies to assess thermal comfort resilience of residential buildings in Barcelona for present and future heatwaves. *Build. Environ.* **2023**, *231*, 110043. [\[CrossRef\]](#)
78. Pioppi, B.; Pigliautile, I.; Piselli, C.; Pisello, A.L. Cultural heritage microclimate change: Human-centric approach to experimentally investigate intra-urban overheating and numerically assess foreseen future scenarios impact. *Sci. Total Environ.* **2020**, *703*, 134448. [\[CrossRef\]](#)
79. Krelling, A.F.; Lamberts, R.; Malik, J.; Zhang, W.; Sun, K.; Hong, T. Defining weather scenarios for simulation-based assessment of thermal resilience of buildings under current and future climates: A case study in Brazil. *Sustain. Cities Soc.* **2024**, *107*, 105460. [\[CrossRef\]](#)
80. Besen, P.; Boarin, P.; Haarhoff, E. Energy and seismic retrofit of historic buildings in New Zealand: Reflections on current policies and practice. *Hist. Environ. Policy Pract.* **2020**, *11*, 91–117. [\[CrossRef\]](#)
81. Gherri, B.; Maiullari, D.; Finizza, C.; Maretto, M.; Naboni, E. On the thermal resilience of Venetian open spaces. *Heritage* **2021**, *4*, 4286–4303. [\[CrossRef\]](#)
82. Rubio-Bellido, C.; Pulido-Arcas, J.A.; Cabeza-Lainez, J.M. Adaptation strategies and resilience to climate change of historic dwellings. *Sustainability* **2015**, *7*, 3695–3713. [\[CrossRef\]](#)
83. Cantatore, E.; Fatiguso, F. An energy-resilient retrofit methodology to climate change for historic districts. Application in the Mediterranean area. *Sustainability* **2021**, *13*, 1422. [\[CrossRef\]](#)
84. Huang, Y.; Wang, F.; Hiscock, A.V.; Satyarthi, J.; Smith, H. Including Embodied Carbon in Assessing Renovation Options for Industrial Heritage Buildings: A Review and Case Studies. *Sustainability* **2025**, *17*, 72. [\[CrossRef\]](#)
85. Green-Mignacca, S.; Rostami, M.; Bucking, S. Towards codification of thermal resilience upgrades in midrise residential buildings: A Canadian archetype energy model approach. *J. Build. Perform. Simul.* **2024**, *1*–23. [\[CrossRef\]](#)
86. Linkov, I.; Bridges, T.; Creutzig, F.; Decker, J.; Fox-Lent, C.; Kröger, W.; Lambert, J.H.; Levermann, A.; Montreuil, B.; Nathwani, J.; et al. Changing the resilience paradigm. *Nat. Clim. Change* **2014**, *4*, 407–409. [\[CrossRef\]](#)
87. Cheye, S.; Adewale, A.A.; Ademola, O.M. Harnessing Artificial Intelligence for Climate Resilience: Analysing the Impact of Climate Change on Sea Level Rise and Precipitation Patterns. *Int. J. Res. Publ. Rev.* **2024**, *5*, 2875–2893. [\[CrossRef\]](#)

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.