ZERO BUILD JOURNAL

INTERNATIONAL SCIENTIFIC FORUM

Year (Yıl) : 2025 Volume (Cilt) : 3 Issue (Sayı) : 2

Electronic Journal
e-ISSN: 2980-0048

ZERO BUILD JOURNAL

AN INTERNATIONAL SCIENTIFIC FORUM

Prof. Dr. Ziya SOGUT
Editor-in-Chief

Prof. Dr. Umit Unver
Owner

ZEROBUILD JOURNAL

INTERNATIONAL SCIENTIFIC MAGAZINE

Call for Papers from ZeroBuild Journal

ZeroBuild Journal (e-ISSN : 2980-0048) is an international, peer-reviewed, electronic journal that publishes studies on Zero Energy Buildings in English (with an extended summary in Turkish). The primary aim of ZeroBuild Journal (ZBJ) is to publish original research papers, short papers, case studies, and review papers that contribute to academic knowledge in theoretical and practical aspects of Building Energy Performance. ZBJ is indexed by SUDOC, Google Scholar, and the Directory of Open Access Scholarly Resources (ROAD). Each paper published in the journal is assigned a unique Digital Object Identifier (DOI) number.

The field of Zero Energy Buildings is interdisciplinary, bringing together Mechanical, Civil, Electrical, Chemical, HVAC, Energy Systems, Environment engineering, and Architecture disciplines. ZeroBuild Journal is significant as it is the first journal specifically focused on Zero Energy Buildings, aiming to inform academics and industry professionals worldwide about scientific and technical developments in the field. ZeroBuild Journal is published twice yearly, in January and July, and can be accessed at https://zerobuildjournal.org.

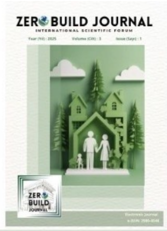
Electronic Journal
e-ISSN: 2980-0048

INDEX - İÇİNDEKİLER

ZERO BUILD JOURNAL

Derleme

Unver ve ark. 03:02 (2025) 41-70



Ukrayna Bina Stokunun Sürdürülebilir Yeniden İnşası İçin Strateji Çerçevesi Geliştirilmesi: Literatür Taraması ve Öneri

Umit Unver[*1,3], Nika Trubina[2,3], Antonín Lupíšek[2,3], Petr Hajek[3], Jan Tywoniak[3]

[1]Yalova Üniversitesi, Türkiye
[2]UCEEB, Czech Republic
[3]Czech Technical University in Prague, Czech Republic
*Sorumlu Yazar: umit.unver@yalova.edu.tr

Öne Çıkanlar:

- Ukrayna için sürdürülebilir yeniden inşa strateji çerçevesi önerildi
- 4 boyutlu ve üniversal bir yeniden yapılanma stratejisi üretildi
- Yeniden yapılanma programının bölgesel olması ve farklı bina tipolojilerini kapsaması önerildi.
- Yeniden yapılanma derhal başlayıp, artan hızla kademeli olarak planlanmalıdır

Geliş Tarihi: 01.03.2025 Kabul Tarihi: 13.04.2025 Doi: 10.5281/zenodo.15211663

Amaç:
Bu çalışma, savaş sonrası Ukrayna'nın bina stokunun sürdürülebilir bir şekilde yeniden inşa edilebilmesi için, mevcut literatürü inceleyerek, uygulanabilir bir temel strateji çerçevesi önermeyi amaçlamaktadır. Yeniden yapılandırma konusunda bu güne kadar yayınlanan, bilimsel araştırmalardan ve aktardıkları tecrübelerden yararlanarak uygun bir stratejisi çerçevesi oluşturmaktır.

Yöntem:
Araştırma, Ukrayna'nın savaş sonrası yeniden inşasıyla ilgili olabilecek yayınlara odaklanmıştır. "Bilim ve mühendislik" dışındaki alanlardan elde edilen yayınlar hariç tutulmuş ve geri kalanlar incelenmiştir. Savaş sonrası Ukrayna'daki bina stokunun yeniden inşası için özel bir strateji çerçevesi tanımlanmak için, araştırma kapsamı diğer yıkım türlerini de kapsamak üzere, afet sonrası yeniden inşa stratejilerini de içerecek şekilde genişletilmiştir.

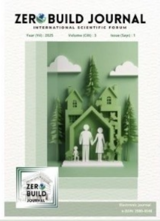
Sonuç:
Yeniden yapılanma için, eyleme hemen başlayıp kademeli olarak artan, hem ekonomik hem de teknik adımları dikkate alan, çok aşamalı bir program uygulanmalıdır. Program Ukrayna'nın her bölgesi için, bölgenin kendi koşullarına ve kaynaklarına göre hazırlanmalıdır. Ayrıca farklı bina tipolojilerini ayrıca kapsamalıdır. Bu çalışmada önerilen strateji, her türlü afette uygulanabilir niteliktedir.

Anahtar Kelimeler: Ukrayna'nın Yeniden Yapılanması, Savaş Sonrası Yeniden İnşa, Yeniden Yapılanma Stratejisi, Afet Sonrası Yeniden İnşa, İhya Planı, Lugano İlkeleri

ZERO BUILD JOURNAL

Review

Unver et al. 03:02 (2025) 41-71



Developing Strategy Framework for the Sustainable Reconstruction of the Ukrainian Building Stock: A Literature Review and Proposal

Umit Unver[*1,3], Nika Trubina[2,3], Antonín Lupíšek[2,3], Petr Hajek[3], Jan Tywoniak[3]

[1]Yalova University, Türkiye
[2]UCEEB, Czech Republic
[3]Czech Technical University in Prague, Czech Republic
*Corresponding Author: umit.unver@yalova.edu.tr

Highlights

- A sustainable reconstruction strategy for Ukraine is proposed.
- A four-dimensional and universal reconstruction strategy was developed.
- The reconstruction program is recommended to be regional and to encompass different building typologies.
- Reconstruction should be planned to commence immediately and intervene with increasing speed.

Received: 01.03.2025 Accepted: 13.04.2025 Doi: 10.5281/zenodo.15211663

Abstract: The term "reconstruction" in this paper refers to the process of rebuilding an object that has been damaged or destroyed, essentially following disasters, in this case unfortunately man-made. This paper highlights the impact of the war in Ukraine on various sectors, including agriculture, energy, education, the environment, and especially the building sector. The objective of the study is to propose a viable basic strategy frame for achieving sustainable reconstruction in Ukraine by reviewing existing literature. The research primarily concentrates on the post-war reconstruction of Ukraine. From the results, papers except from "science and engineering" area were excluded and the rest was reviewed. Despite an extensive literature on post-war reconstruction of various sectors, there was not yet described a specific strategy for reconstruction efforts for building stock in Ukraine. Therefore, the scope of the investigation was expanded to include studies on reconstruction strategies following after disasters. This study introduces a general, sustainable and basic strategy for reconstruction. The proposed strategy considers Gradual, Regional, and Typological dimensions. The outlined strategy can be implemented in the aftermath of diverse catastrophic events, ranging from natural disasters to war-torn cities.

Keywords: Reconstruction of Ukraine, Postwar Reconstruction, Reconstruction of Building Stock, Reconstruction strategy, Post-disaster construction, Revival plan, Lugano principles

CONTENT

1. Introduction

Reconstruction literally means "the process of building or creating something again that has been damaged or destroyed". But the meaning of "something" in this definition and in the context of the Russian invasion of Ukraine is very broad. It covers many areas from agriculture - to energy, from economy - to tourism. In this paper, a literature review will be presented for the Sustainable Reconstruction of Ukraine (SRU). The main aim of the research is to propose an appropriate reconstruction strategy for sustainable reconstruction of the building stock in Ukraine by investigating through the recovery and reconstruction studies.

1.1. Broad effect of the war

In February 2022, the world was shocked by the Russian invasion of Ukraine. War has affected all areas of people's lives and government activities [1]. Deep impact is seen in a wide range of sectors, including agriculture, tourism, the economy, energy, and others. In addition to Ukraine, the harm also impacts the rest of the world, most notably Europe [2]. Scientists are examining the damage and potential solutions to help various sectors get back to normal, or in the ideal case, to improve them to a higher level than they were before the war.

The devastating effect of the war on Ukraine has had a significant impact on the business sector. In the first three months, companies almost halved their activities, although later the retail, white goods, electronics, and jewelry sectors showed signs of recovery. However, the entertainment industry experienced the worst recovery rate. Unfortunately, the interruption of the supply chain, decrease in purchasing power, demand changes, and uncertainty negatively impacted the business world [3]. Agriculture is a crucial industry for Ukraine, one of the world's largest exporters of wheat and fertilizers. The war has had a negative impact on the production of agriculture, most notably food products, consequently making food security a concern for many countries worldwide [4]. The food and agriculture hold great significance in Ukraine's 2030 Sustainable Development (SD) plans. The achievement of other Sustainable Development Goals (SDG) is reliant on reaching SDG2: end hunger [5].

Another important research area is the energy security [6]. The Ukrainian and European energy markets, which were directly and indirectly dependent on Russia due to their dependence on natural gas, are extremely sensitive. The Russia-Ukraine war reveals the need to refocus on geopolitical energy security in Europe and around the world. Countries are trying to transform sustainable and green transition formulation on energy into policy in a shorter time [7].

It is stated that, as Russia during war times, supplied the most of Europe's energy, Europe will continue to face the risks of disruption to its energy supply [8]. In this case, the war acts as a catalyst that accelerates the greening of Europe. The War naturally affects public policy support for policies aimed at phasing out fossil fuels and promoting the introduction of clean energy alternatives. In Switzerland, for example, support for policies to reduce fossil fuels has increased drastically because of the war. Before the war, there was an opinion that Ukraine should develop environmental policies that prioritize climate change. Highlighting the accountability of executive and local government bodies, it was recommended to ensure accountability of executive and local government bodies and a transformational transition to renewable and sustainable development technologies.[9].

The war also affected the education sector. As of 24th February, 2023, a total of 2,772 education institutions were impacted by the war, with 454 buildings destroyed in total nearly 10 percent [10]. Depriving children of education is not an option, which is why educators feel obliged to continue uninterrupted teaching and provide psychological guidance and counseling to their students [11]. These efforts of Ukrainian educators should be supported and the potential of education sector should be enhanced after the war for sustainable recovery and development. In this respect, the priority activity of the Ukrainian state is to develop the education standards in accordance with the best educational practices in Europe [12]. Starting in 2019, the Ministry of Education and Science of Ukraine has successfully attempted to implement educational reform. The key one is the concept of the New Ukrainian School. This concept covers changes in the educational process itself, and it proposes an effective approach to develop “New Educational Space” by retrofitting buildings to enhance energy efficiency, providing barrier-free space and conditions for inclusive education, creating a motivational space, and using modern equipment.

1.2. The Studies on the Sustainable Reconstruction of Ukraine

The focus of this paper is defining a suitable strategy for post-war reconstruction of Ukraine building stock. To summarize the related scientific studies so far, we have reviewed the literature. We used Web of Science (WoS), Scopus and Google Scholar database using the keywords “Ukraine” and “sustainability” and “reconstruction”. Excluded the subject areas: physics, heal, immunology, medicine, nursery, pharmacology, and arts. The publication date was limited to 2022 and 2023 since we were dealing with invasion of Ukraine. In Google Scholar research, the exact phrase of “sustainable reconstruction” was searched since otherwise Google brought more than 66000 results.

Table 1. The papers reviewed on the Sustainable Reconstruction of Ukraine

No	Reference (Source)	Keywords of the papers
1	[13]***	Open innovation, tourism, tourism friendly cities;
2	[14]**	Tourism,
3	[15]*	Rural tourism; environment; Sustainable development
4	[16]*	Agritourism, rural areas, rural green tourism, Sustainable development
5	[17]*	Thermal Engineering
6	[18]**	Heating, Thermal Engineering
7	[19]***	Energy Communities, renewable energy, energy transition
8	[20]**	Renewable Energy, Financing
9	[21]**	Energy and Fuel
10	[2]**	Energy policy, energy security, diversification
11	[6]**	Energy policy, energy security
12	[22]*	Energy and fuel, energy security
13	[8]*	Energy, business, energy market
14	[7]*	Energy security, Sustainable energy transitions
15	[23]*	Renewables, presumption, households
16	[24]*	Renewable energy, circular economy
17	[25]*	Energy, renewable energy, agricultural biogas, economic feasibility
18	[26]*	Climate policy, Public opinion, Renewable energy, Sustainable finance
19	[27]***	Climate change, climate action
20	[28]**	Climate Change, bioclimatic potential
21	[4]*	Circular economy, climate crisis, green industrialization
22	[29]***	Sustainable Development Goals
23	[30]**	Sustainable Development Goals
24	[31]*,**,***	Sustainable Development
25	[32]**	Sustainable Development, Urban Architecture, Medical Centers
26	[33]**	Sustainable development, territorial development, economy
27	[34]**	Decarbonisation, green transition, sustainable development
28	[35]**	Urbanization, sustainable development, environmental policy,
29	[36]**	Urbicide city, urbanization
30	[37]*	City revitalization, industrialization, sustainable development,
31	[38]**	Contemporary Architecture, Philosophy in Architecture, Urban Context
32	[39]*	Sustainable development, regional economy, decentralization.
33	[11]*	Education, sustainable development, professional integrity
34	[40]*	Higher education, funding, sustainable and human development
35	[41]*	Sustainable Development, Financial performance, Financial Resiliency
36	[42]*	Economy, sustainable development
37	[43]*	Sustainable development, public-private partnership, intern. partnership
38	[44]***	Recovery and Reconstruction of Ukraine
39	[45]***	Recovery and Reconstruction of Ukraine
40	[46]***	Recovery and Reconstruction of Ukraine
41	[47]**	Resilience, War-torn, Critical infrastructure, Recovery, Prioritization
42	[48]**	Construction and repair works, road

Table 1. The papers reviewed on the Sustainable Reconstruction of Ukraine (Continued)

No	Reference (Source)	Keywords of the papers
43	[49]**	Logistics, Ukraine
44	[50]*	Smart buildings, reconstruction
45	[12]*	Recovery of education
46	[51]**	Economic recovery, Innovation, Digitalization
47	[52]**	Economic recovery, economy
48	[53]*	Housing, construction market
49	[3]*	Marketing, business, retail, sustainability, economy,
50	[54]*	Housing stock, Repair, Privatization, Tenants, Subsidies
51	[55]*	Sustainable development, small business, economic growth
52	[56]**	Anthropogenic landscapes
53	[57]**	Soil, ecology, agriculture
54	[58]**	Environment, heavy metals, agricultural lands,
55	[59]**	Ecosystem, soil, urban park
56	[60]*	Urban green areas, landscape and recreational zones
57	[61]**	Recycling, Postwar recycling, concrete
58	[62]**	Construction waste recycling
59	[9]*	Environmental policy
60	[63]*	Waste management, sustainable development
61	[64]*	Waste recycling, energy and fuel
62	[65]**	Digitalization of the agricultural land
63	[66]**	Digitalization, food sector, circular economy
64	[67]**	Digitalization, food security, agriculture
65	[5]*	Food Security, sustainable development
66	[68]*	Food security,
67	[69]*	Agriculture, forestry
68	[70]*	Agriculture, climate change actions
69	[71]*	Agricultural sector, agricultural enterprises
70	[72]**	Spatial organization, system development,
71	[73]**	Revitalization of the industry
72	[74]**	Nighttime lighting vs refugee number.
73	[75]*	Law
74	[76]*	Flooding, Ethnic disparity

* Web of Science, ** Scopus, *** Google Scholar

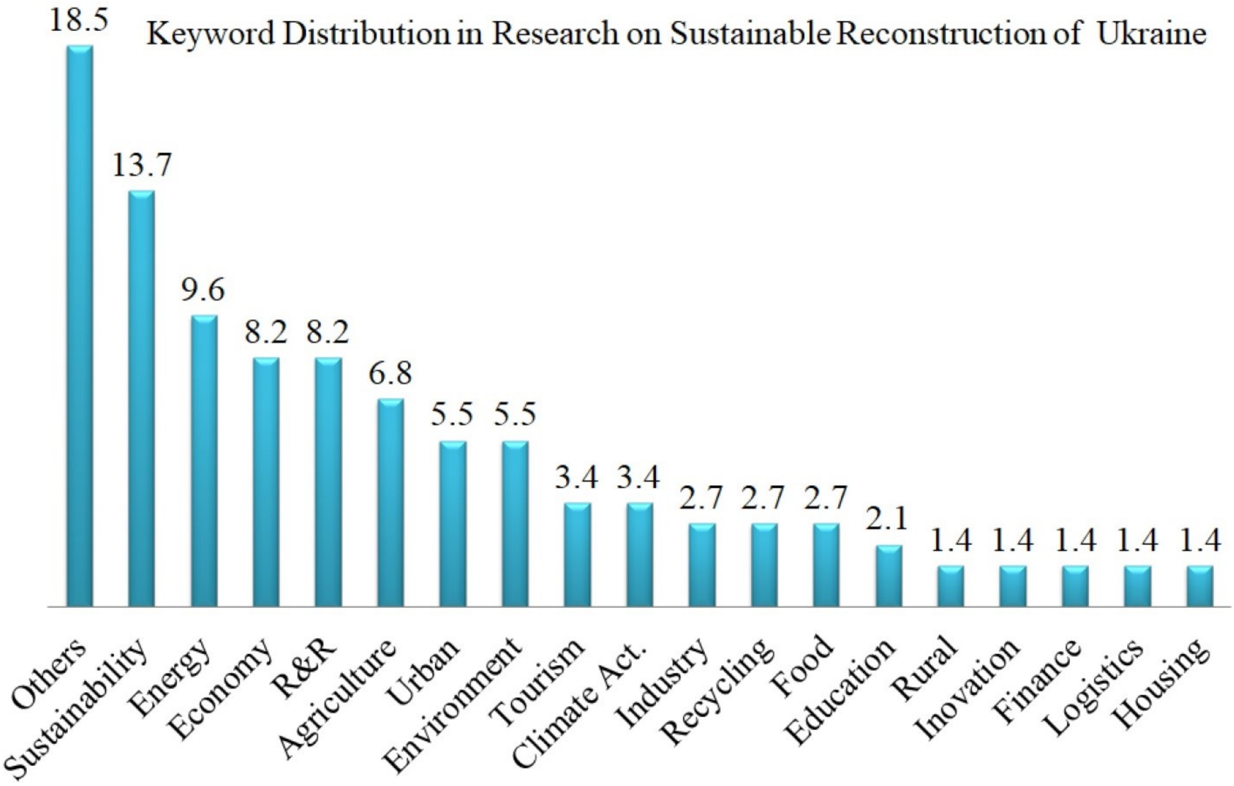


Figure 1. The keywords of the literature reviewed within the research on “Sustainable Reconstruction of Ukraine”

Then we have eliminated the papers which were not related with Russian invasion of Ukraine. Uniting the results and removing the duplicated studies, Table 1 was designed.

Then we grouped the keywords and Figure 1 illustrates the distribution of the keywords. The numbers over the bars show the percentage of the keyword in overall total of all keywords. In Figure 1, the 'Others' column includes keywords that appear only once, such as presumption, public opinion, bioclimatic potential, medical centers, territorial development, architecture, decentralization, professional integrity, human development, partnership, prioritization, smart buildings, housing, subsidies, law, etc. Keywords that appear two or more times are included in Figure 1.

In searches for 'Sustainable Reconstruction of Ukraine,' the most frequent keywords—sustainability (14%), energy (10%), and Recovery and Reconstruction (R&R) (8%)—highlight the crucial link between sustainable reconstruction and energy efficiency. Additional keywords like urban (6%), environment (6%), climate action (3%), and housing (1%) emphasize the need for a holistic approach to rebuilding that considers broader environmental and urban contexts.

The invasion seriously affected Ukraine. Scientists examine each sector separately and offer methods for restructuring the sector. We used the Litmap tool to correlate the articles we encountered during the literature review, to see the relationship between the papers. None of them has a citation link with the other. This is because firstly; the papers were published in the same year after the invasion started on February 2022 and secondly; each study describes an individual content. Moreover, the peer-reviewed literature published with “Ukraine + reconstruction + sustainability” keywords do not help determine a post-war reconstruction strategy. The keywords of the recent studies were not exactly cover sustainable reconstruction but covered similar concepts namely; sustainable development goals, food security, energy security etc. (Fig. 1). However, through 74 relevant scientific papers we investigate, none of the existing studies propose a “reconstruction strategy” for the building stock.

To address this gap, our research focuses on the “Sustainable Reconstruction of Ukrainian Building Stock,” highlighting and encapsulating sustainability, energy, and urban development to tackle the complex challenges of Ukraine's reconstruction.

In this paper, a detailed literature review has been performed on the reconstruction of Ukraine since the beginning of the invasion. Since the publications on Ukraine's sustainable reconstruction are insufficient, the content of the paper has been expanded with the title of “post-disaster reconstruction”. Thus, a basic framework reconstruction strategy was created and introduced. The main contribution of this paper is, providing a universal reconstruction strategy, which can be employed in case of any kind of disasters considering regional development, sustainability and stepwise reconstruction.

2. Reconstruction; Definition and Ukrainian Implementation

2.1. Reconstruction: Evaluation of challenges and recommendations

This paper focuses on drafting the basic principles for the post-war sustainable reconstruction of Ukrainian building stock. Therefore, we will first seek an answer to the question "What is reconstruction, and how is it defined?" before moving on to the question "How exactly can a good sustainable reconstruction strategy be determined?"

Today, due to climate change and other natural causes, we are faced with natural events such as fire, earthquake, flood and overflow more frequently. If necessary precautions are not taken against such natural events beforehand, these events turn into disasters. A disaster can also be anthropogenic, such as war. Whatever the source of the disaster, man-made reconstruction is essential.

If disasters were predictable, it would be much easier to avoid loss and take precautions. However, the reality is unfortunately not like this, and the consequences of disasters can be extremely catastrophic. Some principles and approaches can be used to meet the needs such as food, hygiene and shelter in a planned and programmed manner as soon as possible so that people affected by disasters can survive and hold on to life [77].

Disasters can destroy lives or cities with an impact that lasts for years in a few seconds. This can lead to the destruction of not only human life, but also the economic life. Therefore, restructuring and saving economic enterprises in such disasters are one of the key tasks for the recovery of social life as soon as possible [78].

While cities are being built, each building is designed individually for separate purposes. However, reconstruction after a disaster takes a much shorter time than new construction, and is characterized by inherent complexity and chaos due to its large scale and the need for simultaneous reconstruction of various structures. In such cases, in order not to be insoluble, to save the lives of the most number of people as soon as possible, to fulfill the social life and needs as soon as possible, it is absolutely necessary to prepare in advance, design applicable programs and develop disaster policies [79].

Construction activities in the recovery process are comparatively more intensive and sophisticated than normal construction by nature. After a disaster, many institutions and charities are involved in the reconstruction process. In order for this sometimes chaotic process to be successful, it must be well planned with a multidisciplinary professional team and appropriately designed programs [80]. Government, disaster victims and Non-Governmental Organizations (NGOs) are the main actors in a recovery project and share the responsibilities of program initiation, project initiation, project financing, design, reconstruction, post-project changes. For an unbiased process, it would be helpful to integrate international scientific organizations into the reconstruction plan, so Ukraine's scientific knowledge could be improved with the support of international stakeholders [52]. Beforehand, the factors that will affect success and the success criteria should be determined and the process should be designed accordingly [81]. The most important success factors for post-disaster reconstruction are defined as: Effective organizational regulations, professional management and professional teams, coordination and cooperation, supportive legislation, fast and effective information and communication management key partners clearly defined success criteria, logistics, resource utilization [82]. However, it is important to have an overview of possible major issues or problems for the reconstruction process: financing, relocation, land ownership, construction material, construction cost, construction labor, construction quality, local capacity, charity capacities, coordination, communication, political environment. Without an appropriate disaster management policy, these issues can grow and become unsolvable problems [82]. On the other hand, It has been emphasized that strong leadership and social cohesion are important for disaster preparedness, disaster response, and post-disaster reconstruction [83]. If public institutions and NGOs do not prepare professionally and scientifically for such disasters, the only effect of such a structure is to slow down the vitally important emergency response and enlarge the problem.

The resource that can be used for recovery are listed as: natural resources, cultural resources, human resources, social resources, political resources, financial resources, and structural resources that can support other resources. The reactions of different societies to disasters and the use of resources may be different. The resource planned in disaster preparedness may affect the ability to use resource of all subsequent phases [83]. Unplanned resources may prevent utilization of the other resources. From this point of view, each society needs to prepare differently for each disaster, and it is necessary to plan each of the above-mentioned resources as capital in a multidimensional manner.

Finding appropriate financial resources at the right time in coordination with local governments, identifying users, determining the appropriate assistance method, participation of enough and various stakeholders in the reconstruction, risk and time management are defined as key parameters of the planning stage. During the design phase, selection of suitable sites, problem-free land use, physical plan, quality definitions, determination of suitable construction types, sustainability, reduction of future disaster risks, design according to building typologies, program, resource planning and risk management should be considered. Also, different application methods, management of construction projects, characteristics of materials, procurement and transportation, labor and labor management, delivery, maintenance and after-use evaluation of completed projects, should be considered. The construction phase is not just about returning people affected by the disaster to their normal lives. At the same time, it is a process that provides an opportunity to prepare for the next disaster and reduce the impact of the next disaster with all kinds of measures to be taken [84].

While planning the recovery, the situation of reconstructing in a wider area, scenarios that can solve the "geographical inertia" problem that means the constant occupation of dangerous places, the approaches that will protect the "spirit of the place", sustainable disaster reduction, producing vision, defining the efficiency of reconstruction and increasing its impact should be studied [85]. Recovery opens many windows of opportunities. In the restructuring of the city, if necessary, stylish investment projects should be put on hold and the spirit of the city should be preserved after the urbicide [36].

Advanced and versatile planning is the key factor for disaster recovery that should also cover economic losses. Contrary to physical losses, economic losses continue cumulatively until the end of the recovery process. If these losses are not compensated appropriately and quickly, they may result in the emigration of the citizens [86]. This means that the demographic structure changes affects not only in the location affected by the war or disaster, but also other countries starting from nearby places. As developed countries like Europe or USA attract more attention, they will be the address for resettlement. Similar effects are observed both in the Ukraine war and in Syria. For example, when the Syrian civil war started in 2011, as a first reaction, around 30% of people fleeing the war preferred to seek refuge in 28 EU countries [87].

2.2. Challenges is reconstruction studies performed so far for other disasters

Disasters of all kinds, whether anthropogenic or natural, are projected to increase greatly in the frequency and magnitude of events. The population affected by the increasing disasters in recent years is forced to leave their homes. For example, approximately 17.2 million people were left homeless in 2018, with US$250 billion lost in damages, leaving approximately 26 million people in poverty over the world. Mass deaths also occurred during and after disasters [77]. The International Disaster Database states that between 2000 and 2019, a total of 1.65 billion people worldwide were affected by the floods, causing a total damage of 563 billion USD. Institutions such as the World Bank recommend the use of assessment tools such as Social Impact Assessment tools in the context of "understanding disaster risk" in order to detect disaster effects in a shorter time and better [88]. The Planning for Post-Disaster Recovery and Reconstruction handbook provides policies, the planning process, and more to guide planning for post-disaster recovery and reconstruction [89].

In order to achieve a sustainable recovery, the risks must be known and appropriate structuring must be selected. "Geographical inertia" must be resolved by legislation. If possible, reconstruction plans should be made before the disaster, separately for each disaster type [85]. For example, choosing lightweight structures for a hurricane is not an appropriate selection. The height of the structures planned for the earthquake should be determined according to the frequency of the seismic vibration produced by the region's ground. In post-war reconstruction, the layout of the city should be in such a way to make a military intervention difficult and to facilitate defense.

The "window of opportunity" perspective is the assumption that there is greater potential for resolving social problems after a disaster than before a disaster. Many people hope, after a disaster, that the disaster will accelerate their hopes and plans for change and development. Disasters can revitalize a society, and even restructuring efforts can make society a force for improvement and upgrading [90]. On the other hand, there is no guarantee for this process to be successful and the failure of the process can be due to lack of resources, lack of government support, budget limitations, delay in the process, and lack of community contribution [79].

It is stated that one of the most important topics for post-disaster recovery is logistics [91]. Because, if the roads are damaged in a disaster, losses and damages increase at every stage of the disaster recovery that brings extra burden to the society. In the case of the war in Ukraine and the earthquake that occurred in Turkey, it was observed that not only the damage to roads but also the damage to air, railway and sea transportation increased the losses exponentially.

2.3. Recovery studies performed on Ukraine so far

2.3.1. How to Recover?

Disaster management has three stages and starts before the disaster. The steps are described as: mitigation and preparedness before the disaster, response and post-disaster recovery [44]. Post-Disaster Recovery, on the other hand, is described as a four-stage process. Emergency response, restoration, reconstruction and upgrade [79]. Disaster management and post-disaster reconstruction management can be evaluated together starting from the "Emergency response". In order for the process to be carried out successfully, it is important to have transparency, accountability, clearly defined goals, providing education and guidance to the community, good coordination and cooperation, evaluation and performance measurement [81]. This study provides an example for mitigation and preparedness before the disaster step.

The aim of the reconstruction of all kinds of disasters is to meet human needs and to normalize social life. Therefore, the recovery action begins as soon as the disaster begins with the "emergency response" stage until the social life is enhanced to a better state than before. In this process, all disciplines of management i.e. logistics, information, quality, risk and project must be managed simultaneously and jointly. Therefore, recovery can be defined as an interdisciplinary and cross-sectoral process, meaning that it requires stakeholders from many sectors to come together.

Recovery can be performed much more effectively and accurately with today's technology and decision making techniques. However, no matter how advanced technology is used, an appropriate strategy must be determined, appropriate data must be processed and continuous damage/due diligence assessments must be carried out. Damage/due diligence assessment should take into account the identification of needs, assessment of critical infrastructure, assessment of available resources, and recurrence of damage due to war [47].

For Ukraine's future practice, it is necessary to take into account that the post-disaster recovery process frequently fails due to a lack of finance, insufficient support from the government, lack of funding and supporters, and a lack of community involvement [79]. It should be noted that, the quality of humanitarian aid operations is defined by parameters such as supportive policies, transparent and quality information sharing, response rate and security measures. In addition, there is a gap in the disaster management system in terms of proactive identification of victims, design of strategic programs, flow of funds through innovative platforms to provide adequate assistance to victims [77]. If additional factors like inadequate integration, inappropriate evaluators, corruption, poor communication and coordination, ineffective/wrong planning, and logistics are taken into account, the reconstruction process will unavoidably fail [81]. A simple and convenient way to success can be considered as international cooperation with financial, academic and professional institutions. As an academic institution, our target is to develop an appropriate strategy for reconstruction.

2.3.2. Ukraine Situation and Losses

The invasion killed thousands and started an influx of refugees. By June 2022, about 8 million Ukrainians were internally displaced and by February 2023, other more than 8 million Ukrainians had left the country. It is predicted that about US$80 billion in government funds will be needed for short-term needs within the framework of restructuring for profits-generating industries that are expected to recover and restore crucial public sector assets, such as schools and roads, and speed recovery [74, 92].

As of June 1, 2022, the total damage only in the housing sector is estimated to be USD 39.2 billion. About 817,000 settlements were affected by the war, and 38 percent of them were destroyed beyond repair. The war had significant effects on the urban housing stock [92]. Ukraine's housing stock ages early as a result of a lack of maintenance funding resources. A portion of the pre-war population resided in these inferior technologically constructed homes [50]. The real estate sector was negatively impacted by the political instability and the war has heightened the drama of this scenario. The real estate market is anticipated to contribute greatly to the reconstruction process. It is recommended that land, air, and sea transportation be perfected in order to boost the region's worth and revitalize the real estate market [53].

2.3.3. Energy Stress

Ukraine is energy – dependent country. This dependency threatens both some sectors such as manufacturing and logistics and national security in the country. Its main energy source is natural gas, which is Russian origin. Ukraine consumes 40% of the total energy in the buildings [93]. Similarly, European Union is sensitive in energy issues. EU publishes energy efficiency legislations in buildings, green transition, smart and sustainable growth, and institutional resilience policies. With the "Smart Energy Saving" project developed in this context, it is aimed to reduce the negative effects on energy saving, sustainability and the environment with the subsidy programs supported by the European Union funds [94]. The European Union defines energy efficiency studies as a valuable tool to overcome energy supply challenges. The aim of energy efficiency studies is to contribute to supply security by reducing primary energy consumption and energy imports. Today, Ukraine needs to reduce its dependence on energy both because of the use of energy supply as a weapon against itself and because of its responsibility to fight the climate crisis [93]. The simplest method that countries can implement and develop policies to reduce their energy intensity is the energy efficiency in buildings. With the energy efficiency studies in the buildings, both the economy is contributed in the production phase and massive overconsumption is prevented during the operation phase. Therefore, energy stress leads post-war reconstruction strategies of Ukraine towards energy efficient buildings.

2.3.4. European Integration

The National Council for the Recovery of Ukraine from the Consequences of the War (NCRU) has stated willingness for interregional and cross-border cooperation in the plan “Construction, urban planning, modernization of cities and regions”. The plan also states that international partners are expected to be involved in the recover and improvement process. The war accelerated Ukraine's EU membership and gave a "candidate" status. Therefore, it is expected that European principles, approaches and practices will be further supported in the improvement process [93].

NCRU's “Energy security” plan also envisages financing various projects using the European Green Deal Investment Plan (Invest EU or Just Transition Fund). Significant funds are planned to be allocated, particularly for the implementation of Pilot technologies involving green energy [95]. However, while it is possible for Ukraine to temporarily apply foreign standards, local standards must eventually be amended to align with the EU acquis [92]. In “Construction, urban planning, modernization of cities and regions” plan, NCRU states that the system is not technically ready for EU conformity assessment in the field of construction [93].

NCRU also stated that an inclusive modernization plan integrated with the EU was made in the process of saving economic and social life and improving natural ecosystems. The plan aims for accelerated, sustainable economic growth to ensure people's well-being integrated into European value chains [95]. In the “European Integration” Plan, it is stated that the employment of professionals with the sectoral competence required for EU integration will contribute to the acceleration of the harmonization process [96]. The project "Development of the Interagency Program on Environmental Education and Awareness Raising for Sustainable Development of Ukraine for the Period 2022-2032" was launched for each region of Ukraine. In the project, plans and standards were developed on infrastructure, health services, housing and schools, and digital and energy sustainability in line with European policies. It is planned to increase the quality and effectiveness of environmental education so that the citizens receive sufficient and up-to-date environmental information [96]. In the plan it was stated that Ukraine will be rebuilt in a clean and safe way, ensuring compliance with the Copenhagen criteria for European Union (EU) integration and EU Green Deal [93]. Similarly, the World Bank recommends that the reconstruction process be planned in a way that integrates sustainable development and green transition in line with the 2030 goals and the Paris Agreement [92].

All of the published plans state that the recovery should proceed in parallel with the EU Integration process. At the same time, all plans require technical expert personnel, training support and expert support from international stakeholders. The EU reports that, upon request, Member States will be assisted in establishing national or regional financial support schemes to improve energy efficiency in buildings [97] either directly or through European financial institutions [98].

In the recovery of Ukraine project, an institution namely, “Institute for Sustainable Reconstruction of Ukraine” to provide technical support can be suggested. This Institute will also contribute to the implementation of the principles of partnership, reform focus, transparency, democratic participation, multi-stakeholder participation, inclusiveness stated in the Lugano Declaration. The institute may contribute to the specified issues in the “Construction, urban planning, modernization of cities and regions” Plan, by following actions:

- Build and develop the capacities of authorities and institutions at all levels and ensure cooperation for post-war reconstruction and development.
- Establish a system for regional development institutions,
- Establish a data-based policy and decision mechanism,
- Provide methodological and informational support for the development of local self-government,
- Establishment of education and training programs for the employees of regional development agencies [93].

The EU foresees that the highest improvement can be provided with the easiest intervention in strive against the climate crisis in the housing sector. For this, it has targeted by defining Zero Energy Buildings in Directive 2010/31/EU on the energy performance of buildings that requires member states to provide, on their own terms, appropriate financing and facilitation to promote energy efficiency in buildings and accelerate the transition to zero energy buildings [97].

In Directive 2018/844, the Council announced that Member States should develop long-term renewal strategies to promote skills development and training in the construction and energy efficiency sectors. Accordingly, Member States should establish a long-term strategy for the renewal of the national building stock. These strategies are desired to contain: building stock assessment, determination of renovation approaches related to building type and climate zone, policies to encourage renovations and a forward-looking perspective [98]. Ukraine's improvement project can be staggered until 2050 in parallel with this directive. Accordingly, zero energy buildings are targeted and plans are made considering the building type and climate zone, which is in line with the Ukraine recovery plan [93].

The 2012 directive recommends that member states encourage information on progress made in achieving the targets [99]. The recommendation given here is also consistent with transparency, which is the cause of failure of restructuring projects by [81]. In line with EU jurisprudence, the same work plan can be used for Municipalities of Ukraine. In view of the shortage of experts reported by the NCRU, it may be appropriate to appoint a third-party institute to provide support for specialist staff training and transparent reporting.

40% of energy consumption in Ukraine takes place in buildings. As more than 80% of the buildings were built before 1991, they do not meet modern energy efficiency requirements. The average specific energy consumption in buildings is about 194 kWh/m2. This is 30-50% above the European average. A large part of the heat in buildings is lost due to poor thermal insulation, aging of the installations, wear and inefficiency of use. By implementing the zero energy buildings target to reconstruction strategies,, a 35% increase in energy efficiency in the building sector is targeted with Net Zero Energy Buildings (NZEB) in the medium-term plan [93].

3. Discussion of The Guiding Principles for Ukraine’s Post-War Reconstruction

So far, recovery management, successful planning, factors that can cause failure, Ukraine's NCRU reports and the government's plan, relevant sections in EU legislation have been examined and a general view has been presented. In this section, we will outline the principles of recovery from the general information gathered.

Before the war, the Ukraine published a program and environmental policy on ecological networking, biodiversity conservation, waste management and use. However, political and administrative uncertainties, lack of implementation strategies, and finally Russian aggression hindered the implementation of these programs [9]. From now on, without waiting for the end of the war, reconstruction for a sustainable Ukraine with a renewed strategic roadmap should be started.

Recovery can be defined as change and transformation for the normalization of basic service and social infrastructure [81]. The reconstruction process consists of 4 stages:

i. urgent action,
ii. provision of essential services,
iii. relocation and reconstruction,
iv. developmental reconstruction.

This process can take up to 25 years, depending on the magnitude of the disaster and the affected community [85]. Therefore, a medium-term plan should be made for the rapid restoration of basic infrastructure and services in the process, followed by laying the foundations for sustainable and green growth [39]. However, this plan should be updated with data from the field and continuously improved if necessary. The "policies to be followed" recommended in the studies on the reconstruction of Ukraine can be grouped under 2 main headings: Technical inferences, and administrative inferences.

ADMINISTRATIVE INFERENCES: The reconstruction process is considered by many researchers as an "opportunity to build better". However, if the long-term sustainability of the region's economy is not taken into account, it can lead to a "boom and bust" economy [85]. Therefore, it should be planned very carefully and consciously. Because it's not just the work of rebuilding buildings, it's the process of rebuilding the society. If appropriate techniques are not used, significant problems such as individual inequality, inequality of access to resources, inequality of opportunity and a society vulnerable to disasters can arise.

In the reconstruction process, the regions with the highest economic and political relations with the other countries are the places that the most easily and quickly recovered after the disaster [100]. Therefore, International Public-Private Partnerships (PPP), aimed at strengthening foreign relations, is very important for the restructuring of Ukraine. The establishment of international PPP depends heavily on public support [43]. If the PPP is established with stakeholders like European Union, World Bank, European Bank for Reconstruction and Development (EBRD), it becomes an extremely attractive tool for attracting investment in the reconstruction of social and economic infrastructure.

However, foreign aid programs must be managed in a flexible and transparent way. Administrative and political interventions are among the greatest dangers and obstacles to a successful recovery. If the professional experts' plan is replaced by other personal or political interests, the benefit of some small groups may increase, but the overall benefit of the country will decrease and sustainability will be severely damaged [101]. Furthermore, it is recommended that priority be given to developing cooperation for the effective use of resources and, where possible, providing external assistance in the form of grants [102]. Ukraine should implement changes related to integration with the EU, seriously challenge corruption while receiving support, and establish the framework for restructuring. If the restructuring process is designed to include all stakeholders in accordance with the project management cycle technique, equality, transparency, performing a better and sustainable reconstruction can be achieved [82].

Inference 1: A special-purpose, multi-partner institution can be appointed to avoid the negative effects of domestic politics, facilitate international cooperation, and streamline the project management cycle. This private institution, with global stakeholders as partners, manages and reports on the reconstruction process as a third party. It can provide the speed, transparency, and versatile information flow necessary for the healing process.

World Bank recommends to allow private sector investments and initiatives and to develop support programs for Small and Medium Enterprises (SMEs) for the recovery process. Thus, the building back better process of damaged properties can begin immediately and be increased gradually. This method is also recommended as a suitable method for the equitable distribution of welfare [92].

Inference 2: Starting the action immediately and increasing gradually can be possible with a stepwise program. Both economically and technically steps should be considered. With a gradual planning, better and more sustainable targets can be set. The process can be started to the extent available resources allow.

Social conflicts can slow or halt even the best-planned reconstruction and recovery efforts. If Development Conflict Resolution Techniques are used to prevent such a situation, conflicts can be prevented and sustainable recovery can be achieved. For this, social resources, social networks and social participation can be developed to increase the "capacity of the community" to solve problems and increase well-being during recovery. By this way, an important contribution can be made to build environment for resilience against future disasters [103]. In the draft plan "Reconstruction, urbanism, modernization of cities and regions" published by the NCRU, a sustainable reconstruction should be planned according to the needs of society. Priorities should be determined and ranked, and a project should be prepared by determining technical and commercial strategies. In order to give priority to regional development, national SMEs should be enlarged and the number of companies should be increased and contribution to the economy should be ensured. A modern human-centered approach in line with sustainable development goals should be adopted. Restructuring efforts should be planned to contribute to Ukraine's integration into the European Union [93].

TECHNICAL INFERENCES: Today, there is a chance to integrate Ukraine into the global economy with investments by prioritizing increasing production capacity and transition to the high and green technology [102]. In addition, energy efficiency, smart public transport and climate resilience in urban areas should be prioritized in the rebuilding process. Energy infrastructure should be specially planned and a strategy on agriculture and regional development should be planned [45].

Inspiring by the Marshall plan, the recovery plan should be [46];

i. Organized to promote economic independence,
ii. Administered by Ukraine,
iii. Revised based on ongoing needs assessments
iv. Giving priority to resource conservation and sustainable development.

Inference 3: The strategic plan should be prepared in accordance with the regional development. Thus, the reconstruction will be shaped according to the needs of the region to ensure that it contributes to the economy of that region. Making a special reconstruction plan for each region will shorten the reconstruction period and increase its effect.

In the light of the drawn remarks so far, it was concluded that international organizations should also contribute to the reconstruction process, that the program should be started immediately and accelerated gradually, and that a separate plan should be made for each region. So what should be the upper limit of the plan? To what extent should the plan envisage improving Ukraine's existing building stock? The answers to these questions are actually parallel with the EU integration topic. In the "European

Integration" Draft Plan, it is reported that there is a chance for reconstruction with the philosophy of "build back better" in line with EU environmental and energy policies [96]. In other words, instead of replacing the old one, the reconstruction should be replaced with higher performance, more environmentally friendly and more sustainable [104]. This is basically named as the Concept of reconstruction of buildings after major damage - Build-back strategy.

Figure 2 shows the concept of reconstruction after major damage caused by nature or man-made disaster. The level of performance within the life cycle of a building is gradually reduced due to wear and aging, and when it is reduced below the level set by regulations/standards, the required level needs to be increased by modernization over the standards as part of the upgrade. In the case of an extraordinary damage/disturbance, the level of functional properties may be significantly reduced to the limit, when the building is fundamentally damaged and basic functions are impaired, i.e. performance level of damage state. At this level, the building can often no longer be used, and it is necessary to proceed to a major modernization after the shock phase. Since often such modernization is very time-consuming and costly, it is possible to proceed in several successive stages. The individual phases must be designed in such a way that the subsequent phase could follow without major construction limitations.

In the first step (urgent actions) it is necessary to make the necessary adjustments to ensure the basic functions of the operation of the house. In the second phase (build-back) the modernization is aimed at achieving a quality level corresponding to the state before the damage. In view of the new quality requirements specified in the SDGs, the third step (build-better), should be set at a higher level of the building quality to meet the sustainability requirements.

For example, the "Energy security" Draft Plan states that there is an opportunity to increase energy efficiency in buildings by 13% by rebuilding buildings as NZEB and by thermal modernization of buildings in line with the EU [95]. In addition, within the scope of the EU integration process, there are advanced technology proposals such as smart preparation in line with the EU's 2030 and 2050 targets [50]. The smart readiness proposal is an attractive proposition to set the direction of key information about energy and water consumption of buildings, as well as issues such as policy development and education. Therefore, its inclusion in medium and long-term plans should be considered. However, the implementation of smart features means increased costs, which may not be suitable for a country at war. ***If the reconstruction is designed stepwise, the constructions are planned as "smart ready" in the emergency response step and the smart elements are completed in the medium to long term.***

In this context, it is recommended to prepare a handbook that will include reconstruction projects, architectural design solutions, project sketches and energy efficiency guidelines [93]. However, of course, this handbook should also be prepared by taking into account the regional differences and different objectives of the strategy, and it would be appropriate to divide the plan into steps in line with the "start now and increase gradually" view.

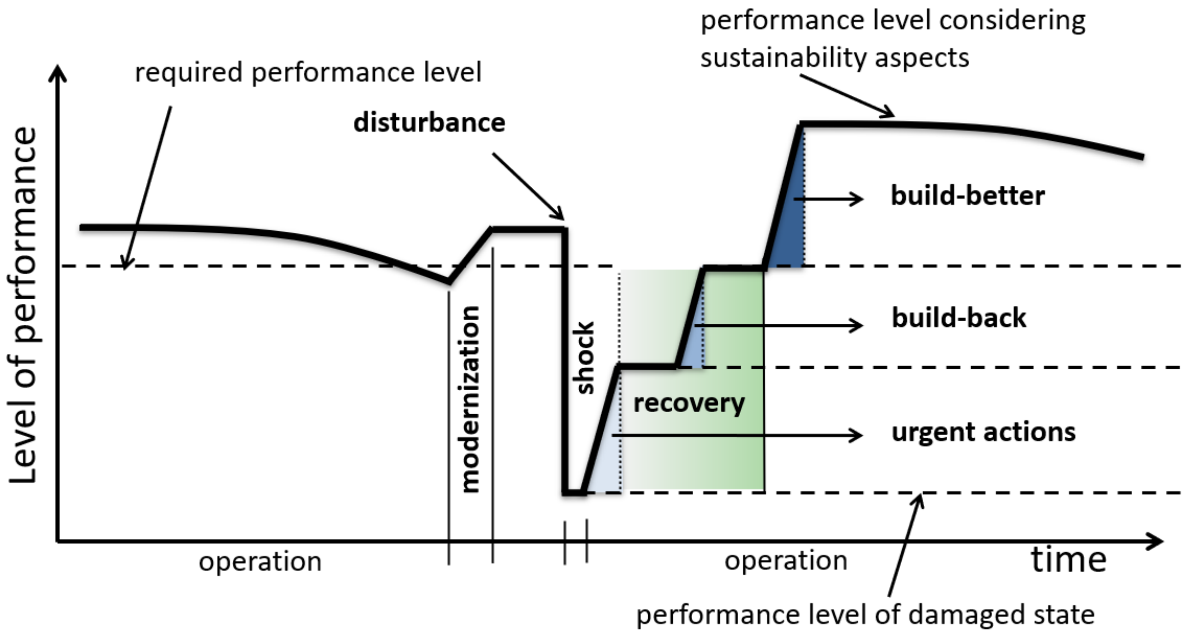


Figure 2 Build-back-better principles within reconstruction strategy

The draft plan "Reconstruction, urbanism, modernization of cities and regions" published by NCRU also provides guidance on some important technical issues. For example, modern, energy efficient and climate resilient reconstruction of social infrastructures such as outdated schools, kindergartens, and health facilities technically necessitates the consideration of climate zones. Region-specific planning of the reconstruction process to support the local economy, for example, designing the reconstruction of buildings with domestic products, increasing and using local and renewable energy sources, is a requirement of local and regional strategy. Therefore, a uniform approach to assessing the suitability of the performance of construction materials is recommended in Ukraine and EU member states [93]. Of course, such an assessment can easily be made by a special purpose third-party independent and international institution.

Inference 4: It is not possible to specify a uniform structure to make climate-resistant and energy-efficient sustainable buildings. Each building type has different needs. This requires consideration of typology for recovery.

4. Concluding Remarks

Various considerations warrant careful attention when contemplating construction projects. Firstly, the risk of demolition due to warfare poses a significant threat to any type of construction. Secondly, it is vital to allocate our limited resources wisely; prioritizing structures that not only restore social stability but also have the potential to generate income for future endeavors. Lastly, given the scarcity of resources, it becomes essential to distribute these resources judiciously among different projects. Taking these factors into account is crucial for effective and efficient reconstruction planning and resource management. Therefore, stepwise planning of reconstruction projects will both increase the efficiency of utilization and contribute to allocate resources in the most appropriate way to all needs.

Four important bullets stand out within the scope of this study. These titles are visualized in Figure 3, each showing a different dimension. The proposed strategic reconstruction bullets include institutional, gradual, regional, and typical planning.

The Institutional bullet aims to establish a dedicated multi-partner institution to spearhead reconstruction, cutting through domestic politics and fostering global collaboration. This body, with international stakeholders, will drive the process with speed, transparency, and comprehensive reporting, crucial for effective recovery.

Figure 3 Reconstruction strategies (Powered by Microsoft Designer).

The stepwise bullet represents the urgent action step of the recovery process. Urgent action includes works that cannot be delayed despite the war. In this step, it can be planned enough to start social life. The immediate action step covers all building typologies, because demolished buildings negatively affect the morale and motivation of war-torn people. Therefore, this bullet involves rebuilding all types of buildings until they come into service. The second step is recommended to plan the reconstruction up to the required performance level. Considering that today's European Union legislation on building energy performance and that the reconstruction period may extend until 2050, it can be foreseen that the required performance level should be kept at the level of passive house standard. The third step describes the "Build Back Better" step, which is the final stage of reconstruction. Since zero emissions are targeted according to European legislation, it is recommended to target buildings that produce their own energy, i.e. zero energy buildings, for this step.

Another bullet in Figure 3 is the building typology. It is planned in line with the zero carbon target, except for some special building types, such as buildings used for historical and agricultural purposes. In other words, they are planned according to energy needs. Since the energy consumption of each building type is different, it is recommended to create a codex according to the building typology when planning the restructuring of the buildings. There are many types of buildings that serve society today such as; housings, educational facilities and public buildings. However, when making a national action plan, it may be appropriate to prepare a separate type of project for each building type.

Regionalism bullet means that buildings should be designed considering the needs and sensitivities of the region. The geographical features of the region are also the key parameters for the energy efficient (passive) design of the building. Passivation techniques such as Solar Wall, the building insulation type and thickness, window to wall ratio should be planned in accordance with the geographical conditions of the region. However, the size of the area (city) and the size of the service that building must provide guide the determination of the building's dimensions. In addition, it is extremely important that buildings are constructed using local materials, both to avoid "boom & boost" economy and to reduce carbon emissions. Therefore, the most important dimension of the reconstruction process that affects social and economic recovery is the regional planning.

Within the scope of this study, we have analyzed more than two hundred papers and identified three important factors for a sustainable and resilient reconstruction of Ukrainian Building stock. These factors can be adopted as a strategic roadmap for not only post-war reconstruction but all other anthropogenic and natural sustainable and resilient post-disaster reconstructions. The described reconstruction model is suitable for planning as emergency response and increase stepwise. The model considers regional characteristics, including materials, which is also suitable for regional development. Also, the proposed strategy is versatile and very useful, as it recommends planning for each building type separately.

5. Acknowledgement

This study has been supported by the Ministry of Education, Youth and Sports within project Mobilita ČVUT-VTA, registration number CZ.02.2.69/0.0/0.0/18_053/0016980.

6. References

[1] O. Khotynska-Nor and A. Potapenko, “Courts of Ukraine in Wartime: Issues of Sustainable Functioning,” *Revista Juridica Portucalense*, vol. 31, no. 31, pp. 218–240, 2022, doi: 10.34625/issn.2183-2705(31)2022.ic-09.

[2] C. Halser and F. Paraschiv, “Pathways to Overcoming Natural Gas Dependency on Russia—The German Case,” *Energies*, vol. 15, no. 14, pp. 1–24, 2022, doi: 10.3390/en15144939.

[3] M. Korneyev, I. Berezhniuk, V. Dzhyndzhoian, T. Kubakh, and K. Horb, “‘Business marketing activities in Ukraine during wartime,’” *Innovative Marketing*, vol. 18, no. 3, pp. 48–58, 2022, doi: 10.21511/IM.18(3).2022.05.

[4] R. Quitzow, O. Renn, and Y. Zabanova, “The crisis in Ukraine: another missed opportunity for building a more sustainable economic paradigm,” *GAIA - Ecological Perspectives for Science and Society*, vol. 31, no. 3, pp. 135–138, 2022, doi: 10.14512/gaia.31.3.2.

[5] O. Kotykova, O. Pohorielova, and M. Babych, “Key Aspects of the Relationship Between Sustainable Development Goals, Food Security and Agricultures in Ukraine,” *European Countryside*, vol. 14, no. 4, pp. 721–752, 2022, doi: 10.2478/euco-2022-0036.

[6] G. Fotis, V. Vita, and T. I. Maris, “Risks in the European Transmission System and a Novel Restoration Strategy for a Power System after a Major Blackout,” *Applied Sciences (Switzerland)*, vol. 13, no. 1, 2023, doi: 10.3390/app13010083.

[7] C. Kuzemko, M. Blondeel, C. Dupont, and M. C. Brisbois, “Russia’s war on Ukraine, European energy policy responses & implications for sustainable transformations,” *Energy Research & Social Science*, vol. 93, no. October, p. 102842, 2022, doi: 10.1016/j.erss.2022.102842.

[8] J. Korosteleva, “The Implications of Russia’s Invasion of Ukraine for the EU Energy Market and Businesses,” *British Journal of Management*, vol. 33, pp. 1678–1682, 2022, doi: 10.1111/1467-8551.12654.

[9] A. Borysenko, Y. Volko, O. Puskina, M. Potip, and Y. Leheza, “Regulatory principles of public administration in the field of state and regional environmental policy as part of the strategy for sustainable development of Ukraine,” *Revista de la Universidad del Zulia*, vol. 13, no. 38, pp. 180–188, 2021, doi: 10.46925/rdluz.3512.

[10] World Bank, Government of Ukraine, European Union, and United Nations, “Ukraine Rapid Damage and Needs Assessment February 2022 – February 2023,” 2023. doi: 10.1596/37988.

[11] X. Ma *et al.*, “Necessity of Post-War Renewal of University Teachers’ Potential in Terms of Sustainable Development in Ukraine,” *Sustainability (Switzerland)*, vol. 14, no. 19, pp. 1–19, 2022, doi: 10.3390/su141912598.

[12] I. Hasiuk, I. Darmanska, M. Mykhaskova, L. Pisotska, and O. Sukhovirskyi, “Assessment of Sustainable

Development of the Educational Sphere of Ukraine in the Paradigm of European Integration Processes," *Revista Românească pentru Educaţie Multidimensională*, vol. 14, no. 2, pp. 136–155, 2022.

[13] A. R. Szromek, B. Walas, and Z. Kruczek, "The Willingness of Tourism-Friendly Cities' Representatives to Share Innovative Solutions in the Form of Open Innovations," *Journal of Open Innovation: Technology, Market, and Complexity*, vol. 8, no. 3, p. 112, 2022, doi: 10.3390/joitmc8030112.

[14] M. Pugachov, V. Pugachov, O. Shevchenko, I. Banyeva, V. Kushniruk, and K. Shvets, "Perspectives for the Tourism and Hospitality Industry in a Globally Competitive Environment," *Economic Affairs (New Delhi)*, vol. 67, no. 5, pp. 907–914, 2022, doi: 10.46852/0424-2513.5.2022.26.

[15] H. Shevchenko and M. Petrushenko, "Rural Tourism within the Sustainable Development Goals: the Case of Ukraine," *SHS Web of Conferences*, vol. 95, p. 01004, 2021, doi: 10.1051/shsconf/20219501004.

[16] T. Sobchenko, T. Mykytsei, N. Zatsepina, A. Krushynska, and T. Samaricheva, "Analysis of Agritourism and Tourism Potential of Rural Areas in the System of Their Sustainable Development: a Case Study of Ukraine," *Scientific Papers-Series Management Economic Engineering in Agriculture and Rural Development*, vol. 22, no. 1, pp. 603–614, 2022.

[17] O. Shevchenko, S. Snizhko, S. Zapototskyi, H. Svintsitska, M. Matviienko, and A. Matzarakis, "Long-Term Analysis of Thermal Comfort Conditions During Heat Waves in Ukraine," *Geographia Polonica*, vol. 95, no. 1, pp. 53–70, 2022, doi: 10.7163/GPol.0226.

[18] A. Polyvianchuk, R. Semenenko, P. Kapustenko, J. J. Klemeš, and O. Arsenyeva, "The efficiency of innovative technologies for transition to 4th generation of district heating systems in Ukraine," *Energy*, vol. 263, no. October 2022, 2023, doi: 10.1016/j.energy.2022.125876.

[19] G. Yiasoumas, K. Psara, and G. E. Georghiou, "A review of Energy Communities: Definitions, Technologies, Data Management," *SyNERGY MED 2022 - 2nd International Conference on Energy Transition in the Mediterranean Area, Proceedings*, pp. 0–5, 2022, doi: 10.1109/SyNERGYMED55767.2022.9941441.

[20] G. Trypolska and O. Riabchyn, "Experience and Prospects of Financing Renewable Energy Projects in Ukraine," *International Journal of Energy Economics and Policy*, vol. 12, no. 1, pp. 134–143, 2022, doi: 10.32479/ijeep.11999.

[21] B. S. Soroka, K. Y. Pyanykh, and V. O. Zgurskyi, "mixed fuel for household gas-powered appliances as an option to replace natural gas with hydrogen," *Sci. innov.*, vol. 18, no. 3, pp. 10–22, 2022.

[22] N. Iwaszczuk, I. Zapukhliak, A. Iwaszczuk, O. Dzoba, and O. Romashko, "Underground Gas Storage Facilities in Ukraine: Current State and Future Prospects," *Energies*, vol. 15, no. 18, 2022, doi: 10.3390/en15186604.

[23] G. Trypolska and A. Rosner, "The Use of Solar Energy by Households and Energy Cooperatives in Post-War Ukraine: Lessons Learned from Austria," *Energies*, vol. 15, no. 20, 2022, doi: 10.3390/en15207610.

[24] G. Trypolska, T. Kurbatova, O. Prokopenko, H. Howaniec, and Y. Klapkiv, “Wind and Solar Power Plant End-of-Life Equipment: Prospects for Management in Ukraine,” *Energies*, vol. 15, no. 5, pp. 1–15, 2022, doi: 10.3390/en15051662.

[25] G. Trypolska, S. Kyryziuk, V. Krupin, A. Wąs, and R. Podolets, “Economic Feasibility of Agricultural Biogas Production by Farms in Ukraine,” *Energies*, vol. 15, no. 1, pp. 1–23, 2022, doi: 10.3390/en15010087.

[26] B. Steffen and A. Patt, “A historical turning point? Early evidence on how the Russia-Ukraine war changes public support for clean energy policies,” *Energy Research and Social Science*, vol. 91, no. July, p. 102758, 2022, doi: 10.1016/j.erss.2022.102758.

[27] O. Brown, A. Froggatt, N. Gozak, N. Katser-buchkovska, J. Orysia Lutsevych, and A. Nixey, “The impact of Russia ’ s war against Ukraine on climate security and climate action Independent Experts ’ Analysis,” 2023.

[28] V. Pichura, L. Potravka, N. Vdovenko, O. Biloshkurenko, N. Stratichuk, and K. Baysha, “Changes in Climate and Bioclimatic Potential in the Steppe Zone of Ukraine,” *Journal of Ecological Engineering*, vol. 23, no. 12, pp. 189–202, 2022, doi: 10.12911/22998993/154844.

[29] P. Heidegger and I. Bakhturidze, “Comments and proposals regarding the theme of UNEA 6 from stakeholders in the European Region,” no. January, 2023.

[30] P. Pereira, W. Zhao, L. Symochko, M. Inacio, I. Bogunovic, and D. Barcelo, “The Russian-Ukrainian armed conflict will push back the sustainable development goals,” *Geography and Sustainability*, vol. 3, no. 3, pp. 277–287, 2022, doi: 10.1016/j.geosus.2022.09.003.

[31] A. Kuzior, I. Pidorycheva, V. Liashenko, H. Shevtsova, and N. Shvets, “Assessment of National Innovation Ecosystems of the EU Countries and Ukraine in the Interests of Their Sustainable Development,” *Sustainability (Switzerland)*, vol. 14, no. 14, 2022, doi: 10.3390/su14148487.

[32] I. Bulakh, “Sustainable Development in the Context of the Architecture of Environmental Friendly Medical Centers in Rural Areas (Case for Ukraine),” *IOP Conference Series: Earth and Environmental Science*, vol. 1111, no. 1, 2022, doi: 10.1088/1755-1315/1111/1/012066.

[33] I. Zablodska, Y. Rohozian, O. Khandii, S. Sieriebriak, and I. Litvinova, “European Experience in the Construction of Territories with Special Economy Regime after an Armed Conflict: A Trajectory of Sustainability,” *Problemy Ekorozwoju*, vol. 18, no. 1, pp. 51–60, 2023, doi: 10.35784/pe.2023.1.05.

[34] V. Koval, O. Borodina, I. Lomachynska, P. Olczak, A. Mumladze, and D. Matuszewska, “Model Analysis of Eco-Innovation for National Decarbonisation Transition in Integrated European Energy System,” *Energies*, vol. 15, no. 9, pp. 1–19, 2022, doi: 10.3390/en15093306.

[35] M. Kryshtanovych, I. Dragan, D. Grytsyshen, L. Sergiienko, and T. Baranovska, “The Public and Environmental Aspect of Restoring Sustainable Regional Development in the Face of the Negative Impact of Military Actions on the Territory of the Country,” *International Journal of*

Sustainable Development and Planning, vol. 17, no. 5, pp. 1645–1651, 2022, doi: 10.18280/ijsdp.170530.

[36] K. Mezentsev and O. Mezentsev, "war and the city : lessons from urbicide in Ukraine," *Czasopismo Geograficzne*, vol. 93, no. 2, pp. 495–521, 2022.

[37] S. Horbliuk, O. Brovko, and S. Kudyn, "Approaches To the Revitalization of Degraded Industrial Zones in Cities of Ukraine," *Baltic Journal of Economic Studies*, vol. 8, no. 1, pp. 36–42, 2022, doi: 10.30525/2256-0742/2022-8-1-36-42.

[38] I. Bulakh, T. Kashchenko, M. Harbar, V. Praslova, Y. Riabets, and V. Divak, "The Integrity of the Artistic Image of the City Based on Symbolization (the Case of Modern Architecture of Dnipro, Ukraine)," *Civil Engineering and Architecture*, vol. 10, no. 3, pp. 874–887, 2022, doi: 10.13189/cea.2022.100310.

[39] O. Borodina, L. Burdonos, V. Stetsenko, and O. Kovtun, "Sustainable Development Management Factors in The Regional Economy of Ukraine," *Economics. Ecology. Socium*, vol. 6, no. 4, pp. 14–26, 2022, doi: 10.31520/2616-7107/2022.6.4-2.

[40] M. Kichurchak, "Factors of Budgetary Funding for Higher Education in the European Countries in the Context of Sustainable and Human Development: Experience for Ukraine," *Financial and credit activity problems of theory and practice*, vol. 2, no. 43, pp. 279–287, 2022, doi: 10.55643/fcaptp.2.43.2022.3540.

[41] M. Mattera and F. Soto, "Dodging the bullet: overcoming the financial impact of Ukraine armed conflict with sustainable business strategies and environmental approaches," *Journal of Risk Finance*, pp. 122–142, 2022, doi: 10.1108/JRF-04-2022-0092.

[42] I. Semenenko, Y. Bilous, and R. Halhash, "The compliance of the regional development strategies and funding with the sustainable development concept: The case of Ukraine," *Green Finance*, vol. 4, no. 2, pp. 159–178, 2022, doi: 10.3934/gf.2022008.

[43] Y. Zaloznova, I. Petrova, and O. Serdiuk, "the Regime of International Private-Public Partnerships in Achieving the Sustainable Development Goals in Ukraine," *Baltic Journal of Economic Studies*, vol. 8, no. 1, pp. 55–61, 2022, doi: 10.30525/2256-0742/2022-8-1-55-61.

[44] A. Nagurney, "Operations Research for the Recovery and Reconstruction of Ukraine," *OR-MS Today*, vol. 49, no. 5, p. 18, 2022, [Online].

[45] I. Holovko and C. Haug, "Rebuilding Ukraine," 2023 Principles of a green post-war reconstruction. Berlin: adelphi consult GmbH.

[46] M. Zholobetska and A. Kotelenets, "Main Directions And Principles of The Reconstruction Plan of Ukraine," *Socio World*, vol. 09, no. 03, pp. 41–47, 2022.

[47] S. A. Mitoulis *et al.*, "Conflict-resilience framework for critical infrastructure peacebuilding," *Sustainable Cities and Society*, vol. 91, no. October 2022, p. 104405, 2023, doi: 10.1016/j.scs.2023.104405.

[48] A. Bieliatynskyi, S. Yang, V. Pershakov, M. Shao, and M. Ta, "Comparative analysis of the influence of various materials on the state of the roadside environment during the road repair," *Environmental Science and Pollution Research*, pp. 15523–15530, 2022, doi:

10.1007/s11356-022-23212-4.

[49] J. A. Dyczkowska and O. Reshetnikova, "Logistics Centers in Ukraine: Analysis of the Logistics Center in Lviv," *Energies*, vol. 15, no. 21, pp. 1–15, 2022, doi: 10.3390/en15217975.

[50] O. Adegov, S. Shekhorkina, M. Babenko, M. Lyahovetska-Tokareva, and O. Kudryavcev, "Smart-Readiness Assessment of a Complex Residential Building in Ukraine," *Slovak Journal of Civil Engineering*, vol. 30, no. 2, pp. 1–11, 2022, doi: 10.2478/sjce-2022-0009.

[51] P. Kulikov, O. Aziukovskyi, O. Vahonova, O. Bondar, L. Akimova, and O. Akimov, "Post-war Economy of Ukraine: Innovation and Investment Development Project," *Economic Affairs (New Delhi)*, vol. 67, no. 5, pp. 943–959, 2022, doi: 10.46852/0424-2513.5.2022.30.

[52] G. C. Pascariu, P. Nijkamp, and K. Kourtit, "Regional Science Knowledge Needs for the Recovery of the Ukrainian Space-Economy: A Q-Analysis," *Regional Science Policy & Practice*, no. January, pp. 75–94, 2023, doi: 10.1111/rsp3.12638.

[53] O. Bochko, N. Kosar, N. Kuzo, I. Bilyk, and O. Zarichna, "Determinants of Housing Construction in Ukraine," *Real Estate Management and Valuation*, vol. 30, no. 3, pp. 1–11, 2022, doi: 10.2478/remav-2022-0017.

[54] A. Shcherbyna, "Towards a concept of sustainable housing provision in Ukraine," *Land Use Policy*, vol. 122, no. September, p. 106370, 2022, doi: 10.1016/j.landusepol.2022.106370.

[55] L. Simkiv, U. Andrusiv, G. Kupalova, N. Goncharenko, O. Dzoba, and O. Yushkevych, "Concentration of Entrepreneurial Activity in the Regions of Ukraine in the Context of Sustainable Development," *Financial and credit activity problems of theory and practice*, vol. 3, no. 44, pp. 347–356, 2022, doi: 10.55643/fcaptp.3.44.2022.3776.

[56] H. Denysyk, V. Kanskyi, V. Kanska, B. Denysyk, and M. Vinnytsia, "Anthropogenic Landscapes of Ukraine and Their Reconstruction," *Czasopismo Geograficzne*, vol. 93, no. 3, pp. 417–433, 2022, doi: 10.12657/czageo-93-16.

[57] O. Kunakh, Y. Zhukova, V. Yakovenko, and O. Daniuk, "Influence of Plants on the Spatial Variability of Soil Penetration Resistance," *Ekologia Bratislava*, vol. 41, no. 2, pp. 113–125, 2022, doi: 10.2478/eko-2022-0012.

[58] D. Breus and O. Yevtushenko, "Modeling of Trace Elements and Heavy Metals Content in the Steppe Soils of Ukraine," *Journal of Ecological Engineering*, vol. 23, no. 2, pp. 159–165, 2022, doi: 10.12911/22998993/144391.

[59] O. Zhukov, O. Kunakh, N. Yorkina, and A. Tutova, "Response of soil macrofauna to urban park reconstruction," *Soil Ecology Letters*, vol. 5, no. 2, 2023, doi: 10.1007/s42832-022-0156-0.

[60] C. Morar *et al.*, "Spatiotemporal Analysis of Urban Green Areas Using Change Detection: A Case Study of Kharkiv, Ukraine," *Frontiers in Environmental Science*, vol. 10, no. March, pp. 1–27, 2022, doi: 10.3389/fenvs.2022.823129.

[61] V. Troian, V. Gots, E. Keita, N. Roussel, U. Angst, and R. J. Flatt, “Challenges in material recycling for postwar reconstruction,” *RILEM Technical Letters*, vol. 7, pp. 139–149, 2022, doi: 10.21809/rilemtechlett.2022.171.

[62] I. Mikhno, N. Ihnatenko, O. Cherniaiev, V. Vynogradnya, D. Atstaja, and V. Koval, “Construction waste recycling in the circular economy model,” *IOP Conference Series: Earth and Environmental Science*, vol. 1126, no. 1, p. 012003, 2023, doi: 10.1088/1755-1315/1126/1/012003.

[63] N. Khumarova and A. Krivenceva, “A Complex Systems Approaches to Sustainable Waste Management: the Case of a Recreational and Tourist Region of Ukraine,” *Economics. Ecology. Socium*, vol. 6, no. 1, pp. 1–10, 2022, doi: 10.31520/2616-7107/2022.6.1-1.

[64] O. Kucher *et al.*, “Energy Potential of Biogas Production in Ukraine,” *Energies*, vol. 15, no. 5, pp. 1–22, 2022, doi: 10.3390/en15051710.

[65] P. Skrypchuk, H. Shpak, V. Skrypchuk, and O. Gorodyska, “Business processes of digitalization of the agricultural land market in Ukraine,” *IOP Conference Series: Earth and Environmental Science*, vol. 1126, no. 1, p. 012001, 2023, doi: 10.1088/1755-1315/1126/1/012001.

[66] L. Lingur, O. Martyniuk, I. Ivchenko, and O. Ivchenko, “Creating a Digital Space of Socially Sustainable Development for Food Enterprises,” *Eastern-European Journal of Enterprise Technologies*, vol. 4, no. 13–118, pp. 22–33, 2022, doi: 10.15587/1729-4061.2022.263540.

[67] Martinho, V.J.P.D.; Cunha, C.A.d.S.; Pato, M.L.; Costa, P.J.L.; Sánchez-Carreira, M.C.; Georgantzís, N.; Rodrigues, R.N.; Coronado, F., “Machine Learning and Food Security: Insights for Agricultural Spatial Planning in the Context of Agriculture 4.0,” *Applied Sciences (Switzerland)*, vol. 12, no. 22, 2022, doi: 10.3390/app122211828.

[68] T. Ben Hassen and H. El Bilali, “Impacts of the Russia-Ukraine War on Global Food Security: Towards More Sustainable and Resilient Food Systems?,” *Foods*, vol. 11, no. 15, pp. 1–17, 2022, doi: 10.3390/foods11152301.

[69] M. Reho, J. Vilček, S. Torma, Š. Koco, A. Lisnyak, and R. Klamár, “Growing of the Containerized Seedlings of English Oak (Quercus robur L.) to Establish Sustainable Plantations in Forest-Steppe Ukraine,” *Forests*, vol. 13, no. 9, pp. 1–11, 2022, doi: 10.3390/f13091359.

[70] A. Ohanisian, N. Levchenko, G. Shyshkanova, G. Abuselidze, V. Prykhodko, and O. Banchuk-Petrosova, “Organic farms are the fundamental basis for the sustainable foreign economic activities of agrarians in Ukraine,” *Environmental and Socio-Economic Studies*, vol. 10, no. 2, pp. 49–61, 2022, doi: 10.2478/environ-2022-0011.

[71] Tetiana Shmatkvska, T. Kulinich, M. Dziamulych, S. Rogach, A. Bilochenko, and O. Serdiukova, “analysis of investment efficiency in the agricultural sector of ukraine on the basis of sustainable,” *Scientific Papers Series Management, Economic Engineering in Agriculture and Rural Development*, vol. 22, no. 3, pp. 649–658, 2022.

[72] M. Habrel, M. Kosmii, and M. Habrel, “Meritocentric Model of Spatial Development in Ukraine: Updating the General Scheme of Planning of the State Territory,” *Spatium*, vol. 2, no. 47, pp. 21–31, 2022, doi: 10.2298/SPAT211123008H.

[73] V. S. Patsiuk, V. L. Kazakov, R. Skorupskas, I. O. Ostapchuk, and A. A. Petrova, “Revitalization of the industrial heritage: Guidelines for Kryvyi Rih,” in *IOP Conference Series: Earth and Environmental Science*, 2022, vol. 1049, no. 1, pp. 1–18, doi: 10.1088/1755-1315/1049/1/012082.

[74] C. Huang *et al.*, “Mapping of nighttime light trends and refugee population changes in Ukraine during the Russian–Ukrainian War,” *Frontiers in Environmental Science*, vol. 11, no. January, pp. 1–13, 2023, doi: 10.3389/fenvs.2023.1055100.

[75] O. Khotynska-Nor and N. Bakaianova, “Transformation of Bar in Wartime in Ukraine: on the Way To Sustainable Development of Justice (on the Example of the Odesa Region),” *Access to Justice in Eastern Europe*, vol. 5, no. 3, pp. 146–154, 2022, doi: 10.33327/AJEE-18-5.2-n000322.

[76] Q. Meng, “A new simple method to test and map environmental inequality: Urban hazards disproportionately affect minorities,” *Land Use Policy*, vol. 122, no. July 2021, p. 106384, 2022, doi: 10.1016/j.landusepol.2022.106384.

[77] S. Modgil, R. K. Singh, and C. Foropon, *Quality management in humanitarian operations and disaster relief management: a review and future research directions*, vol. 319, no. 1. Springer US, 2022.

[78] M. Sapri and S. M. A. Razak, “Asset Management Recovery after the Disater: State of Knowledge,” *MATEC Web of Conferences*, vol. 66, pp. 1–9, 2016, doi: 10.1051/matecconf/20166600067.

[79] M. Enshassi, K. Al-hallaq, and B. Tayeh, “Failure factors facing organizations in post-disaster housing reconstruction projects in Gaza Strip,” *Civil Engineering Research Journal*, vol. 8, no. 5, pp. 1–10, 2019, doi: 10.19080/CERJ.2019.08.555750.

[80] K. N. Khalid, F. A. A. Nifa, R. M. Ismail, and C. K. Lin, “Initial findings on delay factors in the post-disaster housing reconstruction: Local authorities and NGOs perspectives,” *Journal of Engineering Science and Technology*, vol. 12, no. Special Issue 4, pp. 137–146, 2017.

[81] D. Ismail, T. A. Majid, R. Roosli, and N. A. Samah, “Project Management Success for Post-disaster Reconstruction Projects: International NGOs Perspectives,” *Procedia Economics and Finance*, vol. 18, no. September, pp. 120–127, 2014, doi: 10.1016/s2212-5671(14)00921-6.

[82] B. Hidayat and C. Egbu, “A literature review of the role of project management in post-disaster,” *Proc. 26th annual ARCOM conference*, no. September, pp. 1269–1278, 2010.

[83] A. Himes-Cornell *et al.*, “Factors Affecting Disaster Preparedness, Response, and Recovery Using the Community Capitals Framework,” *Coastal Management*, vol. 46, no. 5, pp. 335–358, 2018, doi: 10.1080/08920753.2018.1498709.

[84] J. da Silva, Z. Lubkowski, and V. Maynard, *Lessons from Aceh: Key Considerations in Post-Disaster Reconstruction*, no. January. 2010.

[85] D. Alexander, "Planning for post-disaster recostruction," *Duodecim; laaketieteellinen aikakauskirja*, vol. 111, no. 21, pp. 2078–83, 1995, [Online]. Available: http://www.ncbi.nlm.nih.gov/pubmed/9841166.

[86] A. Nejat and I. Damnjanovic, "modeling dynamics of post-disaster recovery," in *Construction Research Congress*, 2012, pp. 2200–2210.

[87] P. Fargues and C. Fandrich, "Europe Must Take on its Share of the Syrian Refugee Burden, But How?," *Opinions on the Mediterranean*, pp. 1–4, 2012.

[88] P. Aznar-Crespo, A. Aledo, J. Melgarejo-Moreno, and A. Vallejos-Romero, "Adapting social impact assessment to flood risk management," *Sustainability (Switzerland)*, vol. 13, no. 6, 2021, doi: 10.3390/su13063410.

[89] J. Schwab, K. C. Topping, C. C. Eadie, R. E. Deyle, and R. A. Smith, "Planning for Post-Disaster Recovery and Reconstruction," 1998.

[90] E. Passerini, "Disasters as agents of social change in recovery and reconstruction," *NATURAL HAZARDS REVIEW*, vol. 1, no. 2, pp. 67–72, 2000.

[91] E. Hayat and R. D. G. Amaratunga, "Road reconstruction in post - disaster recovery; the challenges and obstacles," in *International Conference on Building Resilience 2011: Interdisciplinary approaches to disaster risk reduction, and the development of sustainable communities and cities*, 2011, [Online]. Available: http://usir.salford.ac.uk/23372/.

[92] World Bank, "Ukraine Rapid Damage and Needs Assessment," 2022. doi: 10.1596/34401.

[93] NCRU, "Draft Ukraine Recovery Plan, Materials of the 'Construction, urban planning, modernization of cities and regions' working group," 2022.

[94] MPO, "National Energy Efficiency Action Plan of the Czech Republic on energy efficiency," 2014. [Online]. Available: https://ec.europa.eu/energy/sites/ener/files/documents/NEEAPCzechRepublic_en2014.pdf.

[95] NCRU, "Draft Ukraine Recovery Plan Materials of the 'Energy security' working group," 2022.

[96] NCRU, *Draft Ukraine Recovery Plan, Materials of the "European integration" working group*, no. July. 2022.

[97] EU CELEX_32010L0031, *on the energy performance of buildings*. 2010, p. L 153 / 13-35.

[98] EU CELEX_32018L0844, *amending Directive 2010/31/EU on the energy performance of buildings and Directive 2012/27/EU on energy efficiency*, vol. 2018, no. May. 2018, pp. 75–91.

[99] EU CELEX_32012L0027, *on energy efficiency, amending Directives 2009/125/EC and 2010/30/EU and repealing Directives 2004/8/EC and 2006/32/EC*, no. October 2010. 2012, pp. 1–56.

[100] S. J. Hogg, "Reconstruction Following Seismic Disaster in Venzone, Friuli," *Disasters*, vol. 4, no. 2, pp. 173–185, 1980, doi: 10.1111/j.1467-7717.1980.tb00271.x.

[101] P. R. Berke, J. Kartez, and D. Wenger, "Recovery after Disaster: Achieving Sustainable Development, Mitigation and Equity," *Disasters*, vol. 17, no. 2, pp. 93–109, 1993, doi: 10.1111/j.1467-7717.1993.tb01137.x.

[102] T. Becker *et al.*, *A Blueprint for the reconstruction of Ukraine*. CEPR Press, 2022.

[103] A. C. Osland, "Resolving land ownership issues for a community water project: A post-earthquake development dispute in rural El Salvador," *Planning Theory and Practice*, vol. 11, no. 1, pp. 47–63, 2010, doi: 10.1080/14649350903538046.

[104] A. Lupíšek, J. Růžička, J. Tywoniak, P. Hájek, and M. Volf, "Criteria for evaluation of resilience of residential buildings in central Europe," *International Review of Applied Sciences and Engineering*, vol. 9, no. 2, pp. 89–93, 2018, doi: 10.1556/1848.2018.9.2.2.

ZEROBUILD JOURNAL

Araştırma Makalesi

Coşkun ve ark. 03:02 (2025) 71-84

Sıfır Enerjili Sağlık Tesislerine Doğru: Ameliyathanelerdeki Enerji Talebini Azaltma

Can Coşkun*, Zuhal Oktay, Veysel Tuna Şaba, Eray Açıkalın, Yağız Fırat Erduman, Enes Börekçi, Cansu Başaran, Ahmet Şen

İzmir Demokrasi Üniversitesi, Mühendislik Fakültesi, Makine Mühendisliği Bölümü, İzmir, Türkiye
*Sorumlu Yazar: dr.can.coskun@gmail.com

Öne Çıkanlar:

- Ameliyathanelerde kullanım dışı saatlerde (gece modu) hava akış hızının azaltılması ile soğutma enerjisi tüketimi 13,4 kWh/m^2 azaltılabilir.
- Hava akış hızında %50 oranında bir azalma ile soğutma dönemi ameliyathane iklimlendirmesinde %11,3 oranında elektrik tasarrufu sağlanabilir.
- Gece modu uygulaması ile hastane elektrik tüketiminde %2,33 oranında iyileştirme sağlanabilir.
- Gündüz saatlerinde soğutma amaçlı elektrik tüketimi, soğutma sezonundaki tüm gün tüketimin %77,3'ünü oluşturmaktadır.

Geliş Tarihi: 08.05.2025 Kabul Tarihi: 20.06.2025 Doi: 10.5281/zenodo.15781980

Amaç:
Bu çalışmada, hastane ameliyathanelerinde havalandırma sistemlerinin işletilmesi bağlamında enerji tüketiminin azaltılmasına yönelik bir öneri sunulmaktadır. Çalışmanın amacı, ameliyathanelerde kullanım dışı saatlerde (gece modu) hava akış hızının azaltılmasının soğutma enerjisi tüketimi üzerindeki etkilerini araştırmaktır.

Metot:
Çalışmada, ameliyathanelerin kullanım dışı saatlerinde iklimlendirmede hava akış oranının %0'dan %50'ye kadar azaltılmasının İzmir ili için enerji tasarrufuna etkisi analitik olarak hesaplanmıştır. Hesaplamalar TS825 standardına uygun olarak gerçekleştirilmiş ve ameliyathane soğutma gereksinimi detaylı bir şekilde analiz edilmiştir.

Sonuç:
Araştırmada, gece modu saatleri 20:00-08:00 olarak belirlenmiştir. İzmir ilinde bulunan bir ameliyathane için soğutma sezonunda, kullanım dışı saatlerde iklimlendirme hava üfleme debisinin %50 oranında azaltılması durumunda, 60 m² büyüklüğündeki ameliyathanede yaklaşık %11,3 (803,3 kWh veya 13,4 kWh/m²) elektrik tasarrufu sağlanabileceği hesaplanmıştır. İncelenen ameliyathane için hava değişim katsayısı 26,2 ACH olarak bulunmuştur. Elde edilen sonuçlara göre, ameliyathanelerde, kullanılmadıkları saatlerde, hava debisi azaltılabilir. Özellikle soğutma ihtiyacının yüksek olduğu gün içi saatlerde sağlanacak tasarruf miktarının daha yüksek olması beklenmektedir. Ameliyathanelerdeki soğutma kaynaklı elektrik tüketiminin yalnızca %22,7'si gece modu saatlerinde (20:00–08:00) gerçekleşirken, kalan %77,3'ü gündüz saatlerinde tüketilmektedir. Özellikle, gündüz soğutması toplam soğutma talebinin %65,7'sini oluşturmasına rağmen, elektrik tüketiminin orantısız bir şekilde %77,3'ünü temsil etmektedir.

Anahtar Kelimeler: Sıfır enerji hastane, Enerji verimli ameliyathane, Ameliyathane soğutması, Sürdürülebilirlik için soğutmanın optimize edilmesi

ZEROBUILD JOURNAL

Research Article

Coşkun et al. 03:02 (2025) 71-84

Towards Zero Energy Healthcare Facilities: Reducing Energy Demand in Operating Rooms

Can Coşkun*, Zuhal Oktay, Veysel Tuna Şaba, Eray Açıkalın, Yağız Fırat Erduman, Enes Börekçi, Cansu Başaran, Ahmet Şen

Izmir Democracy University, Faculty of Engineering, Department of Mechanical Engineering, Izmir, Türkiye
*Corresponding Author: dr.can.coskun@gmail.com

Highlights:

- Cooling energy consumption can be reduced by 13.4 kWh/m² by lowering the airflow rate during non-use hours (night mode) in operating rooms.
- Implementing a 50% reduction in airflow rate results in an 11.3% electricity savings during the cooling period for operating room air conditioning.
- Applying night mode operation can improve overall hospital electricity consumption by approximately 2.33%**.**
- During daytime, cooling accounts for 77.3% of total electricity consumption in the operating room throughout the cooling season.

Received: 08.05.2025 Accepted: 20.06.2025 Doi: 10.5281/zenodo.15781980

Abstract: The concept of zero-energy healthcare facilities represents a crucial strategy in mitigating global warming and combating climate change. This study proposes a method to reduce energy consumption specifically by optimizing the operation of ventilation systems in hospital operating rooms. The primary focus is to evaluate the impact of lowering the airflow rate during non-use hours (referred to as night mode) on cooling energy consumption. Using actual hourly usage data, night mode hours were defined as 20:00 to 08:00. For Izmir province, analysis showed that implementing a 50% reduction in airflow rate during these hours could lead to an electricity savings of 11.3%, equivalent to 803.3 kWh, during the cooling season in a single operating room. These findings demonstrate a significant opportunity to improve energy efficiency in hospital settings by adjusting ventilation system operation according to room usage, contributing to the broader goal of zero-energy healthcare facilities and environmental sustainability.

Keywords: Zero energy hospital, Energy efficient operating room, Operating room cooling, Optimizing cooling for sustainability

1. Introduction

Healthcare facilities are among the highest energy consumers compared to other building types. Hospitals, in particular, have high energy demands due to their 24-hour uninterrupted operations, with energy consumption levels reaching up to 2.5 times those of typical commercial buildings. Major contributors to this high energy use include medical devices, heating and cooling systems, and ventilation systems—critical components for maintaining hygiene and infection control. The substantial energy consumption in healthcare facilities not only raises operating costs but also significantly increases carbon emissions [1]. The World Bank estimates that the healthcare sector contributes approximately 5% of annual global CO_2 emissions, amounting to 2.6 billion metric tons. In the United States, hospitals and clinics are estimated to account for 10.3% of the total energy consumption within the commercial sector [2, 3].

Operating rooms (ORs) are among the most energy-intensive spaces in a hospital, primarily due to stringent ventilation, filtration, pressurization, and thermal comfort requirements. Studies report that ORs consume 3–6 more kWh/m^2 than average hospital areas. For example, a US survey found healthcare buildings average 545 kWh/m^2·yr, whereas a Spanish study measured OR ventilation demands of 1685 kWh/m^2·yr (thermal energy; ~1021 kWh/m^2·yr if adjacent zones like scrub rooms are included). A German measurement of ORs found about 1.2 kWh/m^2·day (438 kWh/m^2·yr). These figures vastly exceed typical commercial building EUIs and illustrate the heavy load of 24/7 high-volume HVAC [4-5].

In recent years, aligned with sustainable development goals and efforts to combat the climate crisis, the concept of the “Zero Energy Hospital” or “Net Zero Energy Hospital” has gained significant interest in the healthcare sector. This approach aims to ensure that hospital buildings generate as much energy annually from renewable sources as they consume, effectively reducing their net energy consumption to zero. This concept is based on two fundamental strategies. The first is to reduce the building’s energy demand by enhancing energy efficiency. Key measures include improved insulation, efficient HVAC systems, LED lighting, smart building management systems, and passive design strategies. The second strategy focuses on supplying renewable energy to meet the remaining energy needs. Renewable technologies such as photovoltaic solar panels, wind turbines, hydrogen, and geothermal systems can be employed to achieve this. It is important to distinguish between net zero energy and carbon neutrality. Net zero energy buildings generate as much energy as they consume over the year from renewable sources, whereas carbon neutral (or net zero carbon) buildings offset the carbon emissions associated with their operations. Carbon neutrality encompasses not only operational energy but also embodied carbon emissions—those associated with the materials and processes involved in construction. Achieving net-zero energy goals in hospitals is a crucial step toward sustainability. However, a broader approach to reducing the carbon footprint of healthcare facilities should also address supply chain management, transportation, waste management, and other operational activities [6]. A key step towards achieving zero-energy hospitals is to improve energy efficiency while increasing the share of renewable energy sources. Among renewables, photovoltaic (PV) solar energy systems are the preferred initial option [7]. New cogeneration systems are also being explored to enhance energy efficiency in hospitals. Assareh and colleagues [8] proposed a novel cogeneration system to meet the energy demand of a hospital in Rome, Italy. Their optimization results indicated that the system could reduce CO_2 emissions by 2.1 tons per hour, with an exergy efficiency reaching 25.1%.

One notable example of a zero-energy hospital worldwide is the Kaiser Permanente Santa Rosa Medical Office Building in California. Covering an area of 8,110 m², this facility is recognized as the first healthcare building in the United States to achieve net zero energy status. The building is entirely self-powered and designed to minimize energy consumption, making it the first proven net zero healthcare building in the country [9]. Another notable example in the United States is the Pueblo Community Health Center East Side Clinic in Colorado. Opened in 2022, it is the first zero-energy outpatient healthcare facility in North America. The 5,950 m² clinic is a conversion of a former supermarket building. Its total on-site energy use is fully balanced by on-site energy production, a fact verified by the New Buildings Institute. The clinic incorporates several energy efficiency measures, including advanced insulation, a ground source heat pump, an energy recovery ventilation system, and LED lighting. Additionally, a photovoltaic (PV) solar panel system with a total capacity of 280 kW was installed on the roof and parking lot. These features contributed to a reduction of over 50% in energy consumption and 66% savings in operating costs. The clinic's total annual energy consumption was 423,024 kWh, while the photovoltaic system produced 435,744 kWh annually, successfully achieving the net zero energy target [10]. Grønnköpingkið University Hospital, located in the Nordic region, is renowned as the greenest hospital in the world. It is a pioneer in sustainable healthcare, minimizing energy consumption through the use of renewable energy systems, high-efficiency insulation technologies, and intelligent building management systems [11].

Various strategies have been developed to transform hospital polyclinic buildings into zero-energy structures, as demonstrated by studies conducted at the University Medical Center in the Netherlands. These studies revealed significant energy-saving potential in hospital buildings and proposed innovative solutions to achieve this goal [12]. A study on a hospital building in Taxila, Pakistan, conducted a techno-economic assessment for converting the facility into a hybrid grid-connected net zero energy hospital. The analysis showed that with a 220 kW photovoltaic solar system integrated with the grid, 70.7% of the hospital's energy demand could be supplied by solar energy, while the remaining 28.3% would come from the grid. The system's payback period was calculated as 2.53 years, with an estimated annual economic gain of 10.24% [13]. The Net Zero Energy Buildings (NZEBs) design approach is widely adopted in Malaysia's construction industry. However, there remain reservations regarding the implementation of NZEB principles specifically in healthcare building projects [14]. In the European Union, reducing energy consumption in healthcare buildings—recognized as some of the most energy-intensive building types—is a key objective of government policy. Sleiman et al. [15] proposed an automated early design support workflow, supported by a suite of tools, to facilitate the development of nearly zero-emission healthcare buildings. Their approach was validated through multiple real-world demonstrations across various countries as part of the European project STREAMER.

Although the concept of zero-energy hospitals has not yet been fully implemented in Türkiye, there are important steps taken in this direction. As of January 1, 2023, buildings with a total construction area of over 5000 m² in Türkiye are required to be constructed as Nearly Zero Energy Buildings (nZEB). This regulation is expected to encourage the integration of renewable energy systems and the adoption of energy-efficient technologies in hospital infrastructure moving forward [16]. In parallel with energy efficiency efforts, a hospital group has tried to start the clean energy era in the healthcare sector. This hospital group, which operates in Türkiye, is investing in Solar Power Plants (SPP) to meet the energy needs of its branch. The installed power of these plants is planned to be approximately 75 MWp. This initiative represents a significant step toward reducing the carbon footprint of healthcare facilities and promoting the use of renewable energy sources in the sector.

The most important innovation of this study is its ability to demonstrate to the Ministry of Health and the Ministry of Finance that energy savings can be achieved in HVAC systems with inverter-controlled motors without requiring any initial investment cost. Turkey has recently prioritized identifying efficiency measures that can be implemented with minimal or no investment. This study presents a significant energy-saving opportunity that aligns well with this national approach. Specifically, by simply adjusting operational schedules via automation systems, existing inverter-controlled HVAC motors can operate in a more energy-efficient "night mode" without additional hardware costs. This makes the proposed method particularly valuable for public sector stakeholders, especially the Ministry of Finance, which is actively seeking low-cost savings solutions. The results of this study can serve as a model for broader implementation across healthcare facilities in Türkiye, potentially leading to substantial cumulative savings in national energy expenditure while maintaining clinical safety standards.

Hospitals are among the structures with the highest energy consumption. A significant portion of this energy, approximately 36%

to 46%, is attributed to air conditioning systems. These systems are essential for maintaining the necessary environmental conditions for patient care, infection control, and equipment functionality. Within hospitals, certain areas are especially critical in terms of air conditioning needs. Operating rooms and intensive care units (ICUs) are priority areas due to their stringent requirements for temperature, humidity, and air quality. Ensuring efficient operation of air conditioning systems in these areas not only helps reduce overall energy consumption but also supports patient safety and health outcomes. Optimizing HVAC performance in these critical zones can involve the use of advanced control systems, energy-efficient equipment, regular maintenance, and real-time monitoring. Hospitals aiming to improve sustainability and reduce operational costs should prioritize these strategies in their energy management plans [17]. Indoor comfort conditions in operating rooms vary depending on the type of surgery performed, and the indoor temperature is typically set between 18-26°C. For example, lower temperatures of 15-18°C are preferred in open heart surgeries to reduce the risk of infection and manage patient body temperature during extended procedures. In contrast, higher temperatures such as 24-26°C are determined for gynecology surgeries where patient exposure is minimized, and thermal comfort is prioritized. These varying requirements necessitate highly flexible and responsive HVAC systems that can maintain precise environmental conditions tailored to surgical needs [18]. However, in practical applications, it is seen that the indoor temperature is mostly left to the preference of the physician performing the surgery. This situation causes temperature settings to change according to personal preferences and energy consumption in air conditioning systems to fluctuate. When examined specifically for state hospitals, it is seen that there is no comprehensive infrastructure that instantly measures indoor conditions and manages the systems according to this data. In current air conditioning systems, the air flow rate into the air ducts is fixed at a certain temperature value; therefore, the air temperatures in operating rooms are generally kept at very low levels. Operating rooms are among the areas where temperature and humidity values in hospitals must be controlled most precisely. In order to change the air flow temperatures and rates in operating rooms according to the need, instant measurements must be made.

2. Material and Method

In this study, the energy performance of an operating room was investigated, and the aim was to reduce energy consumption by making changes to the ventilation system operation. Real-time data from the operating room were used in the study, and the targeted energy savings were calculated analytically.

2.1. Night mode scenario

The capacity utilization rate in operating rooms was investigated. At the studied hospital, by 20:00, the capacity utilization rate in operating rooms drops to 1.9%. In this study, the periods when the operating room utilization rate falls below 2% are defined as "night mode." 99.4% of surgeries are completed between 08:00 and 20:00. Night mode is the hours between 20:00 and 08:00. After midnight, no surgeries are performed except for emergencies, which account for only 0.6% of the total surgeries.

2.2. Cooling load

The energy required for heating and cooling residential buildings can be estimated using the degree-hour method. This approach calculates degree-hour values based on a total of 8,760 hours per year (one full calendar year). Specifically, the cooling degree-hours (°C–hours) can be determined using the following equation [19]:

$$CDH = \sum_{j=1}^{t} (T_{out} - T_{base})_j \quad (1)$$

where T_{out} is the outdoor temperature at hour j, and T_{base} is the base temperature below which cooling is not required. Depending on the outside temperature and the cooling requirements of the operating room, the cooling unit attempts to maintain a consistent supply air temperature. It was observed that this supply air temperature stabilizes at 18.5 °C. For calculation purposes, a base temperature (T_{base}) of 18.5 °C is used. Outdoor temperature data for İzmir were obtained from the Türkiye General Directorate of Meteorology for the year 2024. These temperature records are essential for accurately assessing the thermal load and potential energy savings in the hospital's HVAC system. The data will be used to simulate real-world operating conditions and support climate-based energy optimization strategies. The annual cooling energy demand can be calculated using the following equation:

$$Q_{cooling} = N \cdot CDH + Q_{personnel} + Q_{patient} + Q_{equapment} \quad (2)$$

Here, $Q_{personnel}$, $Q_{patient}$, and $Q_{equipment}$ denote the heat gains from employees, patients, and equipment, respectively.

Thermal gains can be expressed in two main groups as gains consisting mainly of devices and gains from people. Thermal gains can be investigated in two parts as employees and patients. The average number of employees per unit closed area is predicted as 0.1 personnel/m^2. It was observed that there were an average of six healthcare professionals in the operating room where the examination was conducted, depending on the type of surgery. This number includes surgeons, anesthesiologists, nurses, and support staff, and may vary based on the complexity and requirements of each surgical procedure. The presence of healthcare personnel plays a role in determining internal heat gain and ventilation needs within the operating room environment. During the study, it was determined that each healthcare personnel emitted approximately 240 W of thermal heat. Thermal gains from personnel can be calculated using Eq. 3, which takes into account the number of individuals and their average metabolic heat output. This parameter is essential for estimating the internal heat load in the operating room, which directly affects the HVAC system's cooling demand.

$$Q_{employee} = \left[\frac{0.1\ \text{personnel}}{m^2}\right] . \left[\frac{240W}{\text{personnel}}\right] = 24\text{W}/m^2 \quad (3)$$

During the study, it was determined that each patient emitted approximately 260 W of thermal heat. This value represents the average metabolic heat contribution from patients during surgical procedures. It is an important parameter when calculating internal heat loads and designing effective cooling strategies in operating rooms.

$$Q_{patient} = \left[\frac{0.00167\ patient}{m^2}\right] . \left[\frac{260W}{patient}\right] = 0.43\ \text{W}/m^2 \quad (4)$$

The average electrical load density of equipment ($Q_{equapment}$) in the operating room was taken as 171.7 W/m². This value includes the typical power consumption of medical and surgical equipment used during procedures.

The hourly cooling requirements for the operating room, calculated by considering these factors, are presented in Figure 1.

The total cooling load for the operating room was calculated as 41,813 kWh. To verify the accuracy of the calculated cooling load, the total electricity consumption of the HVAC system and the Energy Efficiency Ratio (EER) corresponding to the average outdoor temperature data were utilized. Using this method, the total cooling load was determined to be 43,905 kWh. This calculated value differed from the initially predicted cooling load by approximately 5%, indicating a reasonable margin of validation between the theoretical and empirical approaches.

2.3. Operating Room

An operating room with a ceiling height of 3.5 meters and an area of 60 m² was examined. The cooling unit's hourly volumetric airflow rates ranged between a maximum of 6,050 m³/h and a minimum of 4,400 m³/h, with a nominal flow rate of 5,500 m³/h for the selected air conditioning device. The detailed technical specifications of the air conditioning unit used in the examined operating room are provided in Table 1.

Table 1. Technical Specifications of the Air Conditioning Unit for the Operating Room

Installed Power (kW)	15.63
Cooling Capacity (kW)	28.5
Energy Efficiency Ratio (EER)	3.19

The calculated air change rate for the operating room is 26.2 ACH (Air Changes per Hour). While the volumetric flow rate can be adjusted by up to 10%, it is generally preferred to maintain a fixed volumetric airflow rate to ensure consistent ventilation and maintain the required environmental conditions in the operating rooms.

The total electricity consumption for the operating room during the cooling season was calculated as 7,088.4 kWh. By reducing the airflow rate by 50% during non-use hours (20:00 to 08:00) in the cooling season, a theoretical energy saving potential of 803.3 kWh per operating room was identified (see Fig. 2). The analysis presented in Fig. 2 assumes a 50% reduction in airflow.

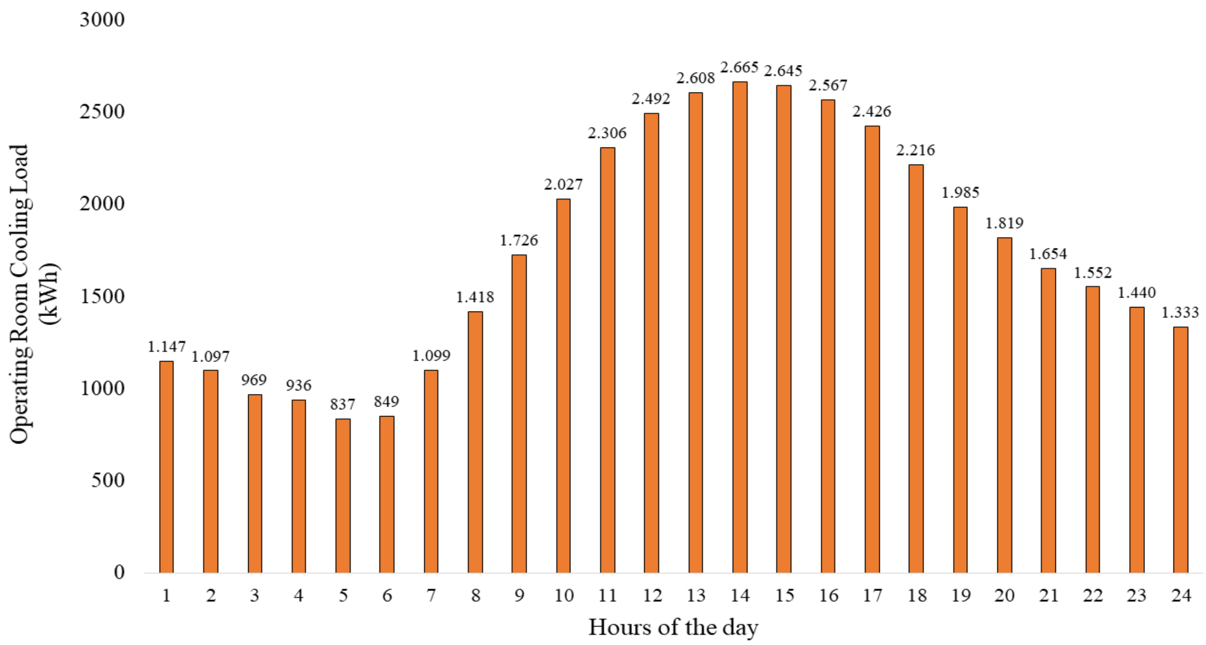


Fig.1. Hourly operating room cooling load

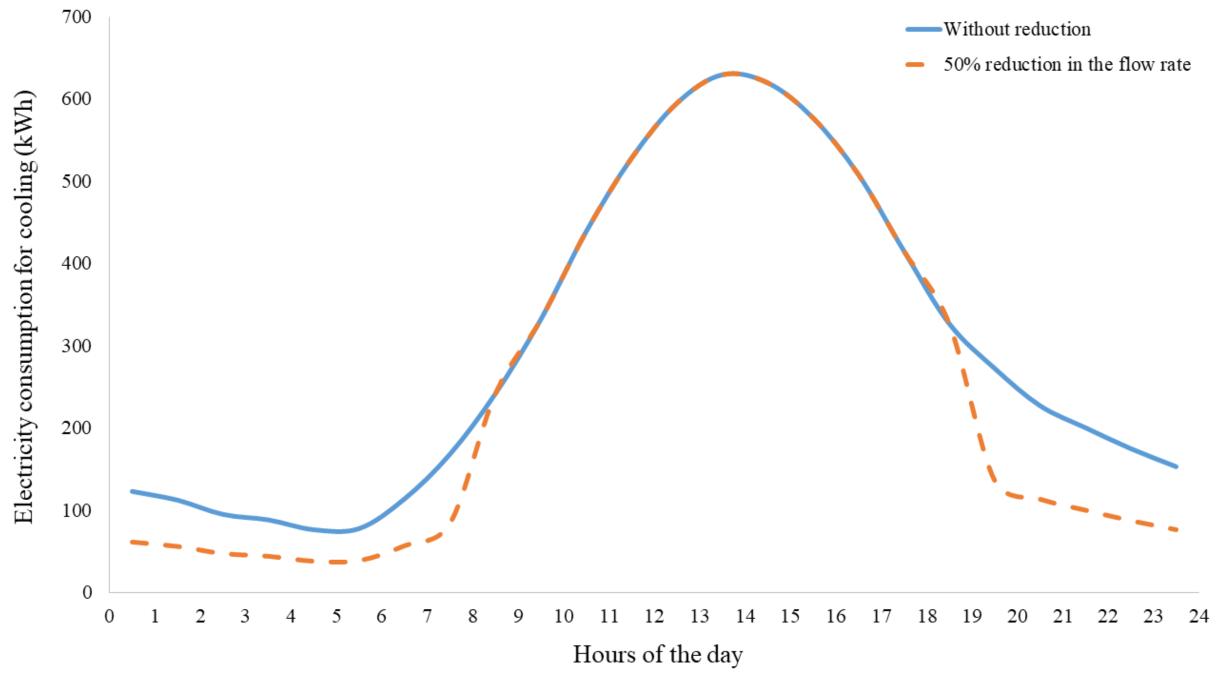


Fig.2. Electricity consumption for an operating room during the cooling season

This assumption is based on the modeling we have conducted as part of the study. The model incorporates various parameters including thermal loads, ventilation requirements, and pressure stability to ensure the feasibility of the proposed airflow reduction.

This theoretical framework serves as a basis for estimating potential energy savings while maintaining operational and safety standards within the operating room.

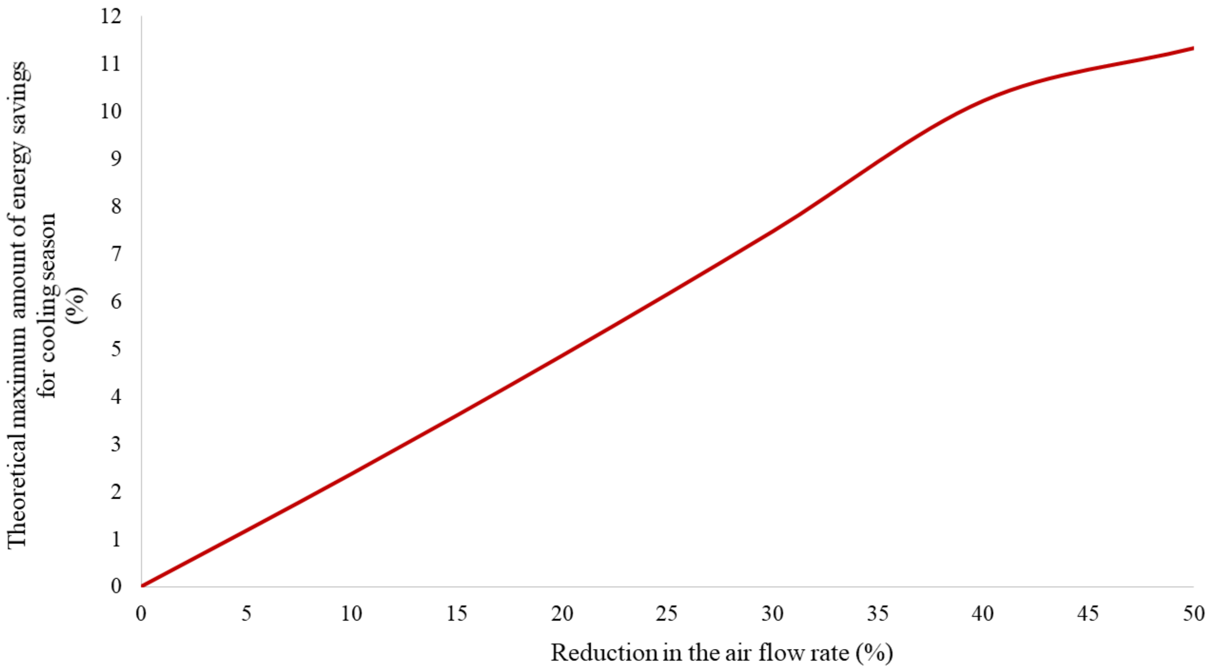


Fig. 3. The theoretical maximum energy savings in operating rooms for night mode ventilation based on different airflow reduction rates.

This relatively modest saving is due to lower outside temperatures and decreased cooling demand at night. At the hospital level, the annual electricity consumption is 1,239 MWh/year, with 255,182 kWh (20.6% of total) attributed to cooling operating rooms. Considering there are 36 active operating rooms in the hospital, the cumulative theoretical maximum energy saving potential reaches 28,918 kWh annually.

Importantly, achieving this saving potential would require only the implementation of automated ventilation control systems, making it a cost-effective and feasible energy efficiency measure

The level of energy savings from operating room cooling can be estimated for any desired airflow reduction rate between 0% and 50% by referring to Figure 3. Implementing night mode ventilation control during the cooling season results in an 11.3% electricity savings for operating room air conditioning. This corresponds to an overall 2.33% reduction in annual hospital electricity consumption.

3. Results and discussion

In this study, the theoretical energy gain that can be achieved for surgeries performed at temperatures between 18 and 19 °C has been calculated. When considering surgeries performed at temperatures ranging from 15 to 26 °C, the potential for energy savings will vary for each operating room depending on its specific temperature conditions. This study focused on a single operating room. In our next phase of research, all operating rooms will be considered, and a comprehensive calculation will be conducted to determine which surgery type corresponds to which temperature range and the associated percentage distribution. Future studies will also aim to determine an average operating room temperature based on the number and types of surgeries performed. Energy savings calculations will then be updated accordingly within this context.

Additionally, this study only assessed data from the province of Izmir. In our subsequent research, different climate zones across Türkiye will be evaluated to determine the energy savings potential for each zone. This will provide a comprehensive overview of the potential savings throughout the country.

We will investigate the thermal comfort conditions in the operating room by using the mood state correction factor proposed by Özkurt et al. [21]. Psychological factors significantly influence thermal sensation and, consequently, HVAC usage behavior. In hospital settings, psychological adaptation—or the changes experienced by individuals during their stay—is a critical consideration. Accounting for these effects is essential when evaluating thermal comfort and optimizing environmental control strategies in healthcare facilities.

According to the Hospital Air Conditioning System Design and Control Principles [20], in accordance with ASHRAE standards, the total ACH in operating rooms in Türkiye should be 25. This standard ensures proper ventilation, infection control, and thermal comfort in critical healthcare environments such as operating rooms. Maintaining this air change rate is essential for meeting hygiene and safety requirements in surgical settings. Future research should focus on the extent to which airflow rates can be further reduced without compromising pressure conditions during non-use periods. Moreover, there is a need to investigate energy-saving opportunities in operating rooms that remain unused during daytime hours, as cooling demand is highest during this period.

Even in night mode, the formation of negative pressure inside the operating room must be strictly prevented. To maintain a minimum positive pressure of 10 Pa within the room, the reduced airflow rate should be carefully determined for each hospital through real-time measurements. Since the architectural layout, HVAC configuration, and usage patterns may vary, different airflow reduction rates will be necessary for each operating room. Therefore, recommending a single, fixed airflow value would not be appropriate from a healthcare safety perspective. Customized analysis and adjustment for each operating room are essential to ensure both energy savings and compliance with hygiene and pressure control standards.

Implementing night mode ventilation control in operating rooms, especially in city hospitals in Türkiye, would be a beneficial step toward reducing energy consumption. With data obtained from such implementations, this strategy could be mandated in the design and construction of future zero energy healthcare facilities, contributing significantly to environmental sustainability and operational cost savings.

There is no additional cost for implementing night mode in systems equipped with inverter-controlled motors. In such systems, only the time intervals need to be configured via the automation system, and the motor speeds can be reduced accordingly. However, for electric motor systems that do not have inverter control, an upgrade to inverter-controlled operation is required. The investment necessary for this conversion will be evaluated, and the payback period will be calculated in detail in future studies. This analysis is essential for understanding the financial feasibility and energy-saving potential of implementing night mode across different types of HVAC systems.

4. Conclusion

Hospitals are among the highest energy-consuming buildings, and generating their own energy from renewable sources offers substantial economic and environmental benefits. The increasing number of successful zero-energy hospital implementations worldwide demonstrates the feasibility of this concept. The following main concluding remarks are drawn from the present study:

- Cooling energy consumption can be reduced by 13.4 kWh/m² by lowering the airflow rate during non-use hours (night mode) in operating rooms. It was calculated that up to 803.3 kWh of energy can be saved annually in an operating room by reducing the airflow rate during non-use hours (night mode), while maintaining the required pressure relationships.
- Implementing a 50% reduction in airflow rate results in an 11.3% electricity savings during the cooling period for operating room air conditioning.
- The measured air change rate was approximately 26.2 ACH, which aligns well with the American ASHRAE standard of 25 ACH for operating rooms.
- Currently, only 22.7% of the total air conditioning electricity consumption in operating rooms occurs during night mode hours (20:00–08:00), while the remaining 77.3% is consumed during daytime. Notably, although daytime cooling accounts for 65.7% of the total cooling demand, it represents a disproportionate 77.3% of the electricity consumption. This is primarily due to the reduced efficiency of cooling units at higher outdoor temperatures during the day, whereas they operate more efficiently at night, resulting in lower electricity usage.
- Applying night mode operation can improve overall hospital electricity consumption by approximately 2.33%.

5. References

[1] C. Coskun, Z. Oktay, H. Özbek, and M.Z. Sogut, "Hospital energy analysis in Turkey," In International symposium on energy management and sustainability, Cham: Springer International Publishing, 2022, pp. 643-654.

[2] D. Serghides, S. Dimitriou, and I. Kyprianou, "Mediterranean Hospital Energy Performance Mapping: The Energy Auditing as a Tool Towards Zero

Energy Healthcare Facilities," In: Sayigh, A. (eds) Sustainable Energy Development and Innovation. Innovative Renewable Energy, Cham: Springer, 2022, doi.org/10.1007/978-3-030-76221-6_50

[3] D. Serghides, S. Dimitriou, and I. Kyprianou, "Paving the Way Towards Zero Energy Hospitals in the Mediterranean Region," In: Sayigh, A. (eds) Green Buildings and Renewable Energy. Innovative Renewable Energy, Cham: Springer, 2020, doi.org/10.1007/978-3-030-30841-4_11

[4] B. Khaled, F. G. Nezami, M. Rasheduzzaman, and B. Deken "Energy Consumption Analysis and Characterization of Healthcare Facilities in the United States," Energies, vol. 12, no. 19: pp. 3775, 2019 doi.org/10.3390/en12193775

[5] A. Cacabelos-Reyes, J. L. López-González, A. González-Gil, L. Febrero-Garrido, P. Eguía-Oller, and E. Granada-Álvarez. "Assessing the Energy Demand Reduction in a Surgical Suite by Optimizing the HVAC Operation During Off-Use Periods," Applied Sciences, vol. 10, no. 7, pp. 2233, 2020 doi.org/10.3390/app10072233

[6] E. Dainese, S. S.W. Walker, W. Maassen, and W. Zeiler, "Towards zero energy hospital buildings: a polyclinic building as case study," E3S Web of Conferences 111:04021, 2019, doi.org/10.1051/e3sconf/2019111040 21

[7] C. Coskun, N. Koçyiğit, and Z. Oktay "Estimation of PV Module Surface Temperature Using Artificial Neural Networks," Mugla Journal of Science and Technology, vol. 2(2), pp. 15-18, 2016 doi.org/10.22531/muglajsci.283611

[8] E. Assareh, A. Keykhah, L. C. Nhien, M. Ghodrat, M. Firoozzadeh, and M. Lee "A proposal on a co-generation system accompanied with phase change material to supply energy demand of a hospital to make it a zero energy building (ZEB)," Energy and Buildings, vol. 318, pp. 114478, 2024, doi.org/10.1016/j.enbuild.2024.114478.

[9] 'Kaiser Permanente: Santa Rosa Medical Office Building Is a Zero-Energy First' Accessed: May. 1, 2025. https://betterbuildingssolutioncenter.energy.gov/solutions-at-a-glance/kaiser-permanente-santa-rosa-medical-office-building-zero-energy-first/printpdf

[10] A. Walker, 'The First Net-Zero Energy Health Center in the U.S. is Here' Accessed: May. 1, 2025. https://www.nachc.org/the-first-zero-net-energy-health-center-in-the-u-s-is-here/

[11] A. Firmo, 'The World's 10 Greenest Hospitals and How They Set the Standard for Green Healthcare' Accessed: May. 1, 2025. https://www.netnada.com/post/the-worlds-10-greenest-hospitals-and-how-they-set-the-standard-for-green-healthcare

[12] E. Dainese 'Towards zero energy hospitals Utrecht University Medical Center case study' 2018, https://pure.tue.nl/ws/portalfiles/portal/108238660/Dainese_0978727.pdf

[13] S. Arif, J. Taweekun, H. M. Ali, and T. Theppaya "Techno economic evaluation and feasibility analysis of a hybrid net zero energy building in

Pakistan: a case study of hospital," Frontiers in Energy Research, vol. 9, 2021, doi.org/10.3389/fenrg.2021.668908

[14] S. Mohamed, H. Z. B. Abdullah, A. N. Masrom, G. K. Chen, and N. Manap "A Systematic Investigation on the Potential of Net Zero Energy Buildings (NZEBs) Design Approach Implementation in Healthcare Buildings," International Journal of Advanced Research in Engineering Innovation, vol. 2, n. 3, pp. 65-77, Nov. 2020

[15] H. A. Sleiman, S. Hempel, R. Traversari, and S. Bruinenberg. "An Assisted Workflow for the Early Design of Nearly Zero Emission Healthcare Buildings," Energies, vol. 10(7) pp. 993, 2017, doi.org/10.3390/en10070993

[16] 'Energy performance regulations in buildings', Accessed: May. 1, 2025. https://www.mevzuat.gov.tr/File/GeneratePdf?mevzuatNo=13594&mevzuatTur=KurumVeKurulusYonetmeligi&mevzuatTertip=5

[17] A. T. Başeğmez and G. Temir, "Calculation of Energy Consumption of a Sample Hospital Building," in Proc. 15th National Plumbing Engineering Congress, Energy Performance in Buildings and Zero Energy Buildings Symposium, pp.1-10, 2023 https://mmoteskon.org/wp-content/uploads/2023/04/2023-BEP-034.pdf

[18] T. Türkay and S. Gerdan, "A Study on the Evaluation of Thermal Comfort Conditions of Operating Room Workers," Ergonomics, vol. 5(2), pp. 120 – 128, 2022

[19] M. A. E. Ertürk, Z. Oktay, C. Coşkun, G. A. Kilic, and A. Dasdemir "A new approach to calculation of energy demand and amount of emission according to different indoor temperature," International Journal of Global Warming, vol. 7(3), pp. 395, 2015

[20] Hospital Air Conditioning System Design and Control Principles. Mechanical Engineering Chamber Publications, pp.142. 2019

https://kitap.mmo.org.tr/hastane-iklimlendirme-tesisati-tasarim-ve-denetim-esaslari

[21] F. Yerlikaya Özkurt, M. F. Özbey, and C. Turhan, "Modeling the mood state on thermal sensation with a data mining algorithm and testing the accuracy of mood state correction factor," New Ideas in Psychology, vol. 76, pp. 101124, 2025, doi.org/10.1016/j.newideapsych.2024.101124

ZEROBUILD JOURNAL

Derleme

Sarı ve Erdoğan 03:02 (2025) 85-104

Sürdürülebilir Yapı Malzemelerinin Seçiminde Çevresel Etki Değerlendirmesi

Mihriban Sarı[1,2] *, Fatma Erdoğan[1,3]

[1]Yalova Üniversitesi, Mühendislik Fakültesi, Yalova, Türkiye.
[2]Betek Boya ve Kimya Sanayi A.Ş., İleri Teknolojiler ve Sürdürülebilirlik Ar-Ge Departmanı, Kocaeli, Türkiye.
[3]EÜAŞ Bursa Doğalgaz Kombine Çevrim Santrali Osmangazi, BURSA, Türkiye
*Sorumlu Yazar: mihriban.sari@betek.com.tr

Öne Çıkanlar:

- Sürdürülebilir yapı malzemelerinin çevresel, ekonomik ve sosyal etkileri çok boyutlu olarak incelendi.
- Geri dönüştürülmüş, doğal ve yerel malzemelerin kullanımına yönelik değerlendirmeler sunuldu.
- Malzeme seçiminde yaşam döngüsü ve gömülü enerji kriterlerinin önemi vurgulandı.
- Uygulamadaki engeller ve çözüm önerileri (teknoloji, teşvik, farkındalık) tartışıldı.

Geliş Tarihi: 17.06.2025 Kabul Tarihi: 21.07.2025 Doi: 10.5281/zenodo.16447143

Amaç:
Bu çalışma, sürdürülebilir yapı malzemelerinin seçiminde çevresel etkilerin nasıl değerlendirileceğini analiz ederek, yapı sektöründe çevre dostu uygulamaların yaygınlaştırılmasına katkı sağlamayı amaçlamaktadır.

Yöntem:
Çalışmada ilk adım olarak, sürdürülebilirlik kavramının tarihsel gelişimini ve yapı sektörüyle ilişkisini daha iyi kavrayabilmek amacıyla, küresel ölçekte bugüne kadar atılmış tüm önemli adımlar ve temel kilometre taşları kapsamlı şekilde analiz edilmiştir. Bu çerçevede, sürdürülebilirliğin çevresel, ekonomik ve sosyal boyutlarıyla nasıl evrildiği ortaya konmuştur. Devamında, ScienceDirect, Google Scholar ve Web of Science gibi saygın veri tabanlarında “sürdürülebilir yapı malzemeleri”, “yeşil malzemeler”, “gömülü enerji”, “LCA” ve “çevresel etki değerlendirmesi” gibi anahtar kelimeler kullanılarak sistematik bir literatür taraması gerçekleştirilmiştir. Toplamda 81 akademik yayın değerlendirmeye alınmıştır. Bu yayınlar, sürdürülebilir malzeme kullanımı, yerel ve doğal kaynakların etkisi, yaşam döngüsü analizleri ve sürdürülebilirlik kriterleri başlıkları altında bütüncül bir yaklaşımla analiz edilmiştir.

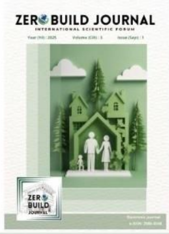
Sonuç:
Sürdürülebilir malzemeler, yaşam döngüsü boyunca düşük enerji tüketimi ve karbon salımı ile çevreye duyarlı çözümler sunar. Geri dönüştürülmüş çelik, hempcrete, doğal lif takviyeli beton gibi malzemeler öne çıkmaktadır. Ancak yüksek maliyet, sınırlı erişim ve sektörel alışkanlıklar önemli engellerdir. Bu zorluklar, teknolojik gelişmeler, teşvik mekanizmaları ve farkındalık artırıcı politikalarla aşılabilir. Malzeme seçiminde sürdürülebilirlik artık isteğe bağlı değil, zorunlu bir kriterdir.

Anahtar Kelimeler: Sürdürülebilir Yapı Malzemeleri, Enerji Verimliliği, Yeşil Tasarım, Sürdürülebilir Yeniden Yapılanma, Çevre Dostu

ZEROBUILD JOURNAL

Review

Sarı ve Erdoğan 03:02 (2025) 85-104



Environmental Impact Assessment in The Selection of Sustainable Building Materials

Mihriban Sarı[1,2] *, Fatma Erdoğan[1,3]

[1]Yalova University, Engineering Faculty, Yalova, Turkey.
[2]Betek Boya ve Kimya Sanayi A.S., Advanced Technologies and Sustainability R&D Department, Kocaeli, Turkey.
[3]EÜAŞ Bursa Doğalgaz Kombine Çevrim Santrali Osmangazi, BURSA, Türkiye

[*] Correspondence: mihriban.sari@betek.com.trk

Highlights

- The multidimensional environmental, economic, and social impacts of sustainable building materials were examined.
- Assessments regarding the use of recycled, natural, and local materials were presented.
- The importance of life cycle and embodied energy criteria in material selection was emphasized.
- Barriers to implementation and proposed solutions (technology, incentives, awareness) were discussed.

Received: 17.06.2025 Accepted: 21.07.2025 Doi: 10.5281/zenodo.16447143

Abstract: This study examines the use of sustainable building materials within the construction sector from a multidimensional perspective. As environmental threats intensify and natural resources become scarcer, sustainable materials are no longer a choice but a necessity. The study evaluates the environmental impacts of these materials throughout their life cycle and assesses their economic viability and social contributions. It also identifies key challenges to their adoption and proposes actionable solutions. The findings demonstrate that sustainable materials are not only environmentally friendly but also economically viable and socially beneficial. These materials serve as a fundamental element in shaping a future-oriented building paradigm and play a crucial role in achieving global sustainability goals.

Keywords: Sustainable Building Materials, Energy Efficiency, Green Design, Sustainable Reconstruction, Environmentally Friendly

1. Introduction

The primary objective of this study is to examine the role of sustainable building material selection in reducing environmental impacts and to evaluate how the use of sustainable materials can be more effectively promoted in the construction sector. The study begins by addressing the historical development of sustainability and its relevance to the building industry, followed by a discussion on how material selection should be guided by sustainability criteria. It then analyzes the environmental, economic, and social benefits of using materials derived from recycled and renewable sources.

Finally, green building certification systems and the multidimensional considerations in sustainable building design are discussed.

Before the Industrial Revolution, limited use of steam-powered machinery and population constraints due to wars and diseases kept environmental impacts relatively low.

However, the industrialization process that began in the early 1900s gained momentum especially after the **1970s**, leading to significant environmental degradation through increased fossil fuel consumption and uncontrolled urbanization [1]. Today, the growing impact of climate change and environmental degradation has made sustainable approaches essential, particularly in the building sector [2]. In this context, adopting sustainable methods in building design and construction is critical for reducing environmental concerns and developing structures that are compatible with ecosystems.

Sustainable construction requires the integration of eco-friendly components. This approach not only mitigates environmental impacts but also brings long-term economic and social benefits [3]. Given the carbon emissions and resource consumption caused by traditional construction materials, the use of sustainable materials has become a necessity rather than a choice [4]. Material selection is one of the most tangible indicators of a sustainable mindset. Engineers and construction professionals are expected to make decisions based on environmental impact, renewability, recyclability, and life cycle analysis [5]. Conscious use of natural resources, waste minimization during production, and ensuring energy efficiency are the core objectives of sustainable material management [6].

Materials derived from recycled and renewable sources support both environmental and economic sustainability [7]. These materials aid in waste management, reduce carbon footprints, lower greenhouse gas emissions, and minimize energy consumption [8]. Sustainable materials offer advantages not only during the production and construction stages but also by lowering maintenance costs during a building's service life. For this reason, construction professionals assess materials based on multiple criteria such as energy efficiency, life cycle costs, and occupant health. At this point, green building certification systems such as LEED provide valuable guidance [9].

Sustainable building design should also address multiple aspects such as climate resilience, water conservation, greenhouse gas reduction, wetland restoration, and public engagement [10]. These elements ensure not only environmental harmony but also long-term societal acceptance of buildings. Due to increasing environmental concerns, the use of sustainable materials is no longer optional but essential [11]. This necessity is not only about protecting nature but also about reducing costs and contributing to global sustainability goals [12].

Sustainability is not only an environmental concept but also encompasses economic development, social equity, and responsible resource management [13]. The most widely accepted definition was provided by the Brundtland Commission: "Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs." Definitions of sustainability emphasize its multidimensional nature and call for integrated approaches that include resource management, social well-being, and environmental protection [14-17]. This integrated perspective has influenced many disciplines, including architecture, urban planning, manufacturing, and energy systems.

The contributions of this study to the scientific literature can be evaluated from several perspectives. First, it provides a systematic review of existing knowledge on the selection of sustainable building materials and addresses parameters directly linked to the environmental impacts of the construction sector from a holistic standpoint.

Table 1. Key Milestones in Global Sustainability Efforts [24]

Year	Event / Document / Organization	Contribution / Description
1972	Club of Rome – The Limits to Growth Report	Warned about the unsustainable nature of economic and population growth on finite planet resources.
1972	UN Conference on the Human Environment (Stockholm)	First global environmental summit; introduced the idea of sustainable development.
1980	World Conservation Strategy	Integrated conservation and development; precursor to sustainability principles.
1987	Brundtland Report – Our Common Future	Defined sustainable development and addressed global environmental and economic challenges.
1992	UN Earth Summit (Rio de Janeiro)	Adopted Agenda 21, Rio Declaration, and principles of sustainability in global policy.
1997	Kyoto Protocol	First legally binding climate treaty to reduce greenhouse gas emissions.
2000	UN Millennium Development Goals (MDGs)	Set 8 global goals including environmental sustainability.
2002	World Summit on Sustainable Development (Johannesburg)	Reviewed Rio commitments; emphasized implementation and partnerships.
2012	Rio+20 Conference	Introduced the concept of the 'green economy'; led to the formation of SDGs.
2015	UN Sustainable Development Goals (SDGs)	Adopted 17 goals to achieve a better and more sustainable future by 2030.
2015	Paris Agreement (COP21)	Legally binding international treaty on climate change to limit global warming below 2°C.
2021	COP26 (Glasgow)	Emphasized net-zero targets, coal phase-down, and climate finance.
2022	Stockholm+50	Focused on environmental protection, climate change, and sustainability on the 50th anniversary of the 1972 Stockholm Conference.
2023	COP28 (Dubai)	Included the first official mention of fossil fuel phase-out; global stocktake initiated.
2024	COP29 (Baku, Azerbaijan)	Focused on carbon markets, climate finance, adaptation, and loss and damage frameworks.
2025	UN Sustainable Development Summit (New Delhi, India, March 5–7)	Assesses global SDG progress, proposes acceleration strategies, and reinforces 2030 Agenda commitments.

Second, it offers a practical evaluation framework for construction professionals by combining current trends in sustainable material management with the criteria of green building certification systems. The originality of this study lies in its comprehensive approach to sustainable material selection—not only from an environmental standpoint, but also by considering economic, social, and ethical dimensions.

The integration of these elements, which are often addressed separately in the literature, into a unified model distinguishes this work from previous studies and enhances its scientific contribution.

2. Historical Development of the Concept of Sustainability

Many of the environmental and social problems faced today stem from the long-term consequences of the industrialization process that accelerated in the 1970s, which were not sufficiently anticipated at the time [18]. Before the Industrial Revolution, factors such as the absence of steam-powered machines, population limitations due to wars, and relatively low levels of consumption helped keep environmental problems at a minimum [19].

However, over time, the diversification and expansion of industrial sectors, combined with rapid and unplanned urbanization, led to an irregular pattern of global growth [20]. This was accompanied by a rising population growth rate and increasing pressure on natural resources, resulting in serious disruptions to ecological balance [21].

In particular, the intensive use of non-renewable energy sources and natural raw materials has triggered a range of complex issues that threaten both nature and human life, including global warming, environmental pollution, and the loss of biodiversity [22]. These developments have made sustainability-oriented solutions unavoidable and have necessitated global cooperation [23].

In this context, under the leadership of the United Nations (UN), sustainability-focused research has been conducted at local, national, and international levels. Various conferences addressing environmental, economic, and social challenges have been organized. These meetings have played a crucial role in defining sustainable development goals and shaping environmental policies (see Table 1).

3. Components of Sustainability

Sustainability consists of three interrelated dimensions: environmental, economic, and social sustainability. These components ensure that sustainable development is addressed through a holistic approach [25].

- **Environmental Dimension:** Environmental sustainability is based on the conservation and renewal of natural resources. It aims to protect environmental heritage for future generations while also focusing on improving environmental values and maintaining the balance of natural ecosystems. Practices such as protecting biodiversity, reducing waste, and using renewable energy sources fall within this dimension [26].
- **Economic Dimension:** Economic sustainability focuses on creating income and employment opportunities to ensure the long-term economic well-being of societies. It involves planning economic activities in ways that do not harm natural resources, supporting local development, and using resources efficiently [27].
- **Social Dimension:** Social sustainability seeks to promote equality, justice, and

quality of life among individuals and communities. It includes ensuring access to essential services such as health care, education, security, and housing for all, as well as protecting gender equality and cultural diversity. This dimension aims to strengthen the social fabric of communities and enhance social cohesion [28].

When these three dimensions are considered together, sustainability emerges as a holistic approach that encompasses not only environmental protection but also economic development and social justice.

Figure 1 visually presents the key factors that make up each component, while Table 2 summarizes the main benefits of sustainability for society, the environment, and the economy.

While the concept of sustainability generally represents a holistic approach encompassing environmental, economic, and social dimensions, its tangible impacts are most

Table 2. Key Benefits of Sustainability

ENVIRONMENTAL BENEFITS	ECONOMIC BENEFITS	SOCIAL BENEFITS
Protection of ecosystems and enhancement of biodiversity	Reduction of operating costs	Improvement of air, thermal, and acoustic environments
Improvement of air and water quality	Increase in property value and income	Enhanced user comfort and health
Reduction of solid waste	Improved employee productivity and satisfaction	Reduced pressure on social infrastructure
Conservation of natural resources	Improved economic performance	Contribution to overall quality of life

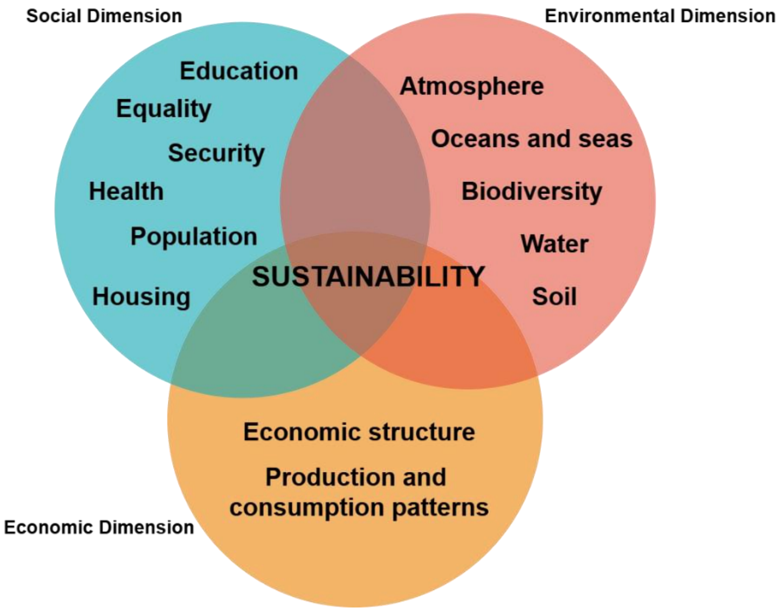


Figure 1. Key Factors of Sustainability Components (Haştemoğlu, 2006)

evident at the sectoral level [29]. In particular, the construction sector plays a critical role in sustainability due to its intensive use of natural resources, energy, and land [30]. Therefore, integrating sustainability principles into the construction industry is of great importance. One of the most effective ways to achieve this integration is by considering sustainability criteria in the selection of building materials [31]. The following section examines how building materials can help reduce environmental impacts while also contributing to long-term economic efficiency and social well-being.

4. Evaluation of Building Materials from a Sustainability Perspective

The concept of sustainable built environment refers to systems that can maintain their existence indefinitely without causing depletion of the resources that sustain them, and without any deterioration in their fundamental properties [32]. This approach aims for buildings to possess not only physical durability but also long-term environmental, economic, and social balance.

Sustainable building materials, on the other hand, are materials that consume minimal energy throughout their lifespan and do not harm the environment or human health at any stage—from raw material extraction, processing, use, maintenance, and repair to final disposal [33]. These materials are often referred to as "green building materials" and hold a significant place in today’s world, where natural resources are increasingly limited.

Green building materials contribute to sustainable development goals by minimizing environmental impacts [34]. Therefore, in the selection of building materials, it is essential to consider not only traditional criteria such as performance, quality, aesthetics, and cost, but also sustainability indicators [35]. In this context, the fundamental characteristics of sustainable building materials include the following:

- They do not contain toxic components and therefore pose no harm to human health [36].
- Their recyclable or reusable nature helps minimize waste generation [37].
- At the end of their useful life, they do not damage the natural environment [38].
- When sourced from local materials and producers, they reduce the carbon footprint and support the regional economy [39].

In assessing the environmental impacts of buildings, it is important to consider not only the properties of the materials used but also the entire life cycle of the building. The life cycle encompasses all stages from the extraction of raw materials, through the construction and usage phases, to the final demolition and disposal [40-42].

This life cycle can be examined in three main phases:

i. **Pre-construction Phase** – Involves raw material acquisition, production, and transportation processes [43].
ii. **Construction Phase** – Includes the construction process and the maintenance and repair activities carried out throughout the building’s lifespan [44].
iii. **Post-construction Phase** – Covers demolition, waste management, and recycling activities following the end of the building’s service life [45].

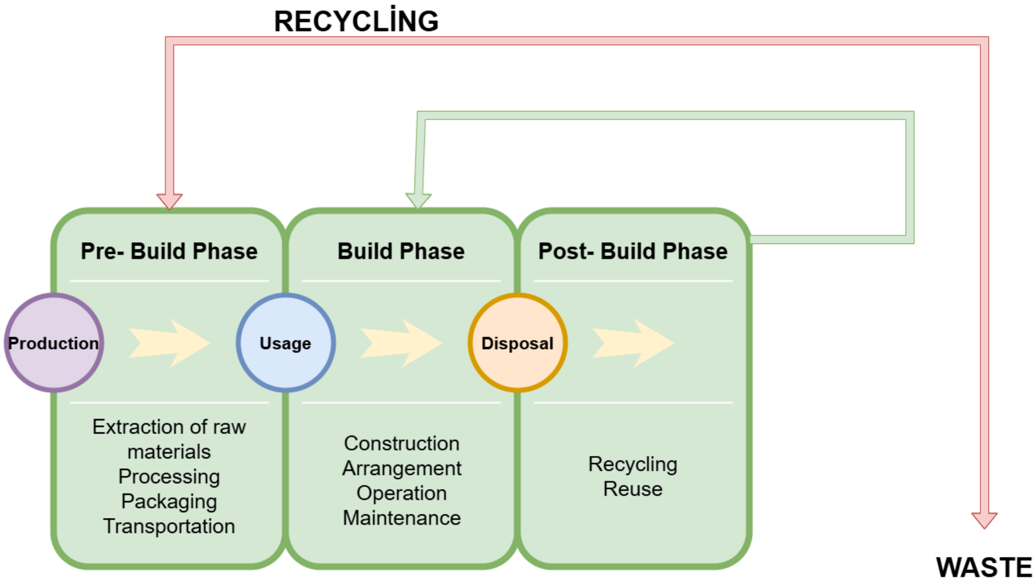


Figure 2.Life cycle of building materials [19]

The details of these three phases and the associated criteria for sustainable building materials are presented in Figure 2.

Adopting this cyclical approach in building design and material selection is of critical importance for reducing environmental impacts and ensuring the efficient use of resources. Sustainable built environment refers to the integration of sustainable development principles into the entire construction cycle of a building and its infrastructure—from the planning, design, and construction phases to the extraction and processing of raw materials, usage, demolition, and subsequent waste management. The initial step in this process involves improving the quality of building materials and enhancing the reliability and efficiency of construction practices. At the same time, environmental impacts, technological advancements, resource consumption, and socio-economic conditions must also be taken into account [46].

One of the primary goals in the construction sector should be to reduce resource consumption. In this context, applicable strategies may be implemented either directly or indirectly [47]. These strategies can be summarized as follows:

- **Reducing material waste:** Preventing material waste during construction offers both economic and environmental benefits. It contributes to the global reduction of construction waste, lowers overall costs, and helps make housing more affordable [48].
- **Use of recycled materials:** Effectively utilizing recycled materials in the construction sector is a powerful strategy for reducing environmental impacts. This approach offers numerous advantages, including the conservation of natural resources, reduced need for landfill disposal, lower energy consumption, and the prevention of pollution resulting from manufacturing processes. It also supports the development of more durable building materials [49].

Improving energy efficiency: Reducing energy consumption in buildings and minimizing the embodied energy of construction materials are key objectives.

Table 3. Sustainability Criteria [51, 52]

DIMENSION	CRITERIA
ENVIRONMENTAL	Is there a reduction in waste?
	Can air pollution be prevented?
	Is the produced material toxic to the environment?
	Does it reduce CO_2 emissions?
	Does it help preserve existing biodiversity in nature?
	Does the material have harmful effects on soil quality?
	Does the material absorb environmental odors?
	Is the produced material recyclable?
	Does it have high reusability?
	Can visual pollution be prevented?
	Does it prevent noise pollution?
	Is the amount of energy consumed low?
	Can it be obtained from natural and local resources?
	Can water pollution be prevented?
ECONOMIC	Can the energy consumed during transport and storage of raw materials be minimized?
	Can transportation costs be reduced?
	Is maintenance and repair easy?
	Is it durable and long-lasting?
	Does it enable the use of fewer materials in goods and service delivery?
SOCIAL	Is the material suitable for the social fabric of the region?
	Can it provide a healthy environment?
	Does the material ensure safety for humans?
	Does it meet housing needs?
	Can it support social balance such as education, cultural activities, suitable jobs, and homes?
	Does it support the local workforce?

Measures to achieve these goals include the adoption of alternative energy sources, enhancement of insulation systems, and increased efficiency in lighting and water heating systems [50].

- **Water conservation:** Efficient water use can be achieved through technologies such as rainwater harvesting systems, greywater reuse, water-saving fixtures, and automatic shut-off taps [51].

- **Durability and maintenance:** Ensuring that buildings are durable and long-lasting is critical to a sustainable construction industry. A structure's ability to maintain its performance throughout its service life should be considered from the design stage. Additionally, buildings should be adaptable and convertible to meet changing needs, maintenance costs should be optimized, and technologies that offer cost-effective solutions throughout the life cycle should be prioritized [52].

In the selection of construction materials, in addition to conventional parameters such as performance and cost, sustainability criteria must also be taken into account. These criteria are detailed in Table 3.

In line with this approach, the concept of embodied energy has emerged as a critical metric for evaluating the environmental impacts of building materials. Embodied energy refers to the total amount of energy consumed throughout all stages of a material's life—from raw material extraction to manufacturing and transportation. This concept enables a more holistic assessment of the overall environmental impact of materials [53].

Table 4 presents the embodied energy values (in MJ/kg) for various commonly used building materials. These values vary significantly depending on the type of material. For instance, a natural and minimally processed material such as adobe block contains only 0.47 MJ/kg, whereas structural steel, which requires high temperatures and energy-intensive processes, reaches up to 35.00 MJ/kg.This stark contrast clearly illustrates the influence of material selection on sustainability. For example, in the production of a structural element weighing 10 tons, using adobe blocks would require approximately 4,700 MJ of energy, whereas the same weight in steel would demand as much as 350,000 MJ—a more than 70-fold increase. Therefore, embodied energy values go beyond being mere numerical indicators and become strategic decision-making tools in the design phase, directly impacting the environmental footprint of a building [54]. The Victoria University of Wellington in New Zealand has provided the following embodied energy coefficients for selected building materials:

As illustrated in Figure 3, environmental considerations in sustainable material selection encompass a wide range of factors including health (e.g., air quality and reduction of VOCs), community impact (e.g., local sourcing and inclusivity), carbon footprint, energy efficiency, and life cycle aspects such as production, usage, and disposal.

Table 4. Embodied Energy Coefficients of Selected Building Materials (MJ/kg)

Material	Embodied Energy (MJ/kg)
Adobe block	0.47
Concrete block/brick	0.94
Ceramic brick	2.50
Glazed brick	7.20
Cement	7.80
Glass	15.90
Steel (structural)	35.00

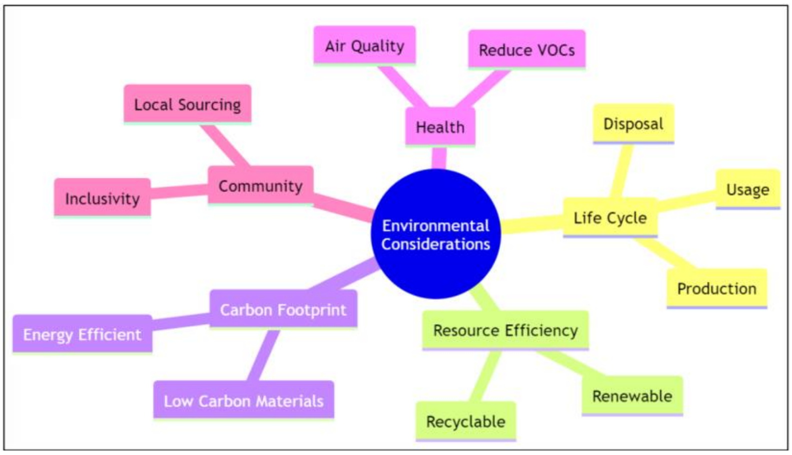


Figure 3. Environmental Assessments of Sustainable Materials

Figure 4. Economic Benefits of Sustainable Materials

The figure highlights how these interconnected elements contribute to resource efficiency and environmental Sustainability [55].

As illustrated in Figure 4, the economic benefits of sustainable materials are multifaceted. In addition to technical advantages such as energy efficiency, low maintenance costs, long-term savings, and durability, external factors like government support, increasing market demand, and regulatory policies also contribute to the financial attractiveness of sustainable materials. Although they may have a high initial cost, the decreasing cost of materials over time and the competitive edge they offer support the widespread adoption of sustainable built environment practices [56].

5. Challenges and Proposed Solutions

The adoption of sustainable materials in building design and construction brings with it a number of significant challenges. One of the most prominent obstacles is the limited availability of such materials—an issue that is particularly evident in regions where sustainable practices have not yet been fully integrated into supply chains [57]. Although these materials are highly favored for their renewable and recyclable nature, the lack of widespread accessibility leads to increased costs, rendering them unaffordable for many construction projects [58].

The potential of sustainable materials to reduce greenhouse gas emissions and other environmental harms has been scientifically demonstrated. However, their high costs and limited supply often deter construction companies and developers from using them on a large scale [67]. Furthermore, the construction industry has traditionally relied on conventional methods and materials. Industry leaders and practitioners often show reluctance to move away from these traditional approaches, making the integration of sustainable materials into mainstream construction practices more difficult [58].

One of the key solutions to these challenges lies in the continuous advancement of technology. Technological innovation plays a crucial role in lowering the cost and improving the availability of sustainable materials [59]. For instance, developments in materials science and manufacturing processes can reduce the carbon content of construction materials, allowing for the creation of more environmentally friendly products while also enabling more cost-effective production [60]. Additionally, improvements in supply chain logistics could facilitate the distribution of these materials to regions where they are currently scarce. This would help reduce overall costs and make sustainable materials a more competitive alternative to traditional ones [59]. Moreover, advances in technology are expected to enhance the quality and durability of sustainable materials, making them more suitable for long-term building projects.

Another effective approach to overcoming resistance in the construction industry is raising awareness about the long-term benefits of sustainable materials. Industry leaders and practitioners need to be informed about the financial, environmental, and social advantages of these materials, as many still lack sufficient knowledge regarding the potential cost savings and increased property value associated with sustainable building practices [61]. This awareness can be enhanced through industry conferences, educational programs, and collaborations with environmental organizations that advocate for sustainable built environment practices.

Moreover, public policies and government incentives can play a crucial role in accelerating the widespread adoption of sustainable materials. Regulations that mandate the use of such materials in certain types of construction projects, as well as financial incentives for developers who meet sustainability criteria, can encourage the industry to embrace these materials more broadly [62]. Such policies help alleviate cost-related concerns and foster broader acceptance of sustainable materials across the construction sector.

6. Investigation of Building Materials According to Sustainability Criteria

Within the scope of sustainable building design, various applications have been developed to reduce environmental impacts, increase energy efficiency, and minimize the use of natural resources. In this context, the use of local, natural, and recycled materials provides significant environmental and socioeconomic benefits. Utilizing locally sourced materials helps reduce energy consumption associated with transportation and production, while also supporting local employment and contributing to regional development [63].

6.1 Recycled-Based Building Materials

Recycling is one of the fundamental components of the green building approach. Reusing waste construction materials allows for the conservation of natural resources, and the reduction of mining activities and environmental pollution. In particular, reprocessing demolition debris into recycled concrete bricks is an effective method for decreasing both energy consumption and waste generation [64].

6.2 Fiber-Reinforced Concrete Applications

Fiber-reinforced concrete, obtained by adding natural or synthetic fibers to the concrete matrix, exhibits superior properties in terms of tensile strength, crack resistance, and overall durability. These concretes are especially preferred in structures exposed to harsh environmental conditions, such as marine structures, bridges, and industrial floors. Concrete reinforced with natural fibers derived from coconut, bamboo, or even human hair presents compelling alternatives from an environmental sustainability perspective [65].

6.3 Alternative Brick and Block Systems

Numerous natural and low-energy materials have been developed as alternatives to conventional bricks and blocks used in the construction sector:

- **Sandbag construction systems** involve stacking polypropylene or geotextile bags filled with locally available sand, offering an economical and eco-friendly building method [66].
- **Adobe bricks** are traditional building materials produced by mixing earth and water and drying them in the sun, based on local production and low energy consumption [67].
- **Compressed Stabilized Earth Blocks (CSEB)** are structural elements produced using modern stabilization techniques and are advantageous due to minimized transportation costs via on-site production [68].
- **Compressed sand bricks**, produced from a mixture of river sand and cement, are suitable in regions where proper soil is not available [69].
- **Hydraform bricks**, made by hydraulically compressing soil mixtures with a small amount of cement, are notable for their low embodied Energy [70].
- **Fly ash bricks**, manufactured by converting industrial waste from thermal power plants into cement-based bricks, offer a low-cost alternative, albeit with limited areas of application [71].

6.4 Natural and Renewable Resource-Based Building Materials

- **Hempcrete** is a lightweight, breathable, and highly thermally insulating natural building material made from a mixture of hemp hurds and a lime-based binder [72].
- **Bamboo**, due to its high tensile strength and rapid growth rate, can be used as a structural component in sustainable built environment [73].

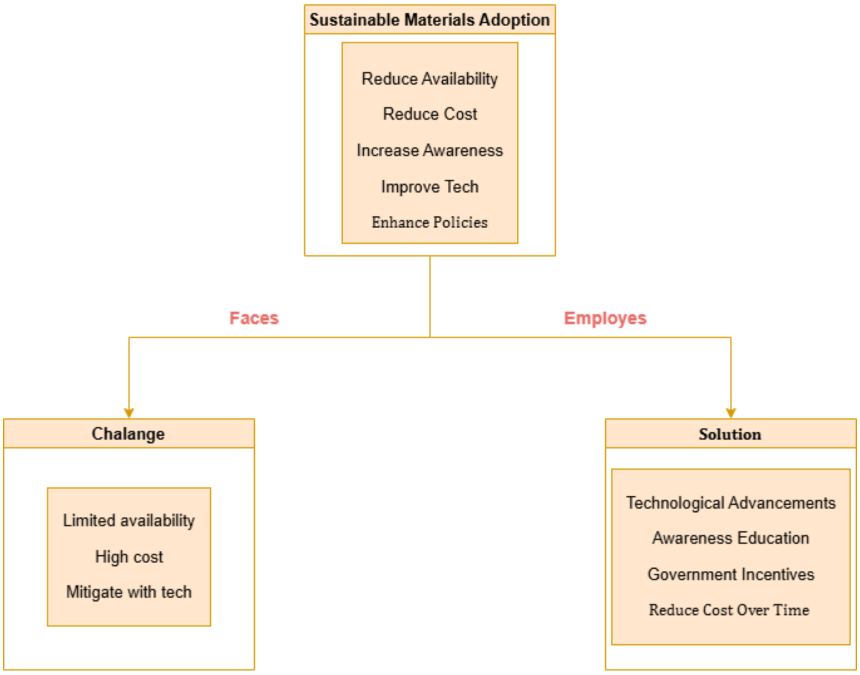


Figure 5. Challenges and Solutions in the Adoption of Sustainable Materials

- **Straw bales** are a low-cost solution commonly used for insulation, particularly in rural areas, and enable the reuse of agricultural waste [74].

6.5 Other Sustainable Material Approaches

- **Recycled aggregates**, obtained by reprocessing construction and demolition waste, are commonly used in infrastructure applications such as backfilling and concrete production [75].
- **Recycled plastics** provide durable and long-lasting solutions in areas such as flooring systems and piping [76].
- **Low-VOC paints**, which emit minimal volatile organic compounds, contribute to indoor air quality and are considered user-health-friendly sustainable materials [77].
- **Natural and recycled insulation materials**, including cellulose, sheep wool, cork, and cotton, offer environmentally friendly options that improve energy Efficiency [78].

These examples demonstrate that sustainability in the construction sector involves more than just energy-efficient design strategies—it is also directly influenced by material selection. Utilizing local resources, reusing waste materials, and opting for natural-based products not only help reduce environmental impacts but also contribute to long-term economic and social sustainability. For instance, natural-based materials like hempcrete are notable for their low energy requirements during production and their capacity to sequester carbon. Likewise, industrial by-products such as fly ash can be repurposed into building materials, reducing waste and preserving natural resources. Additionally, natural fiber-reinforced concretes offer eco-friendly alternatives to traditional reinforced concrete. In this context, material choices clearly play a critical role in achieving holistic sustainability in building design and construction.

7. Discussion

The environmental benefits of sustainable materials in the construction sector are substantial. Numerous studies have employed the Life Cycle Assessment (LCA) methodology to evaluate the environmental impacts of various materials. These assessments typically consider parameters such as carbon footprint, resource depletion, and energy consumption. The findings indicate that sustainable materials such as recycled steel, low-carbon concrete, and bamboo can reduce greenhouse gas emissions by up to 50% compared to conventional materials like traditional concrete and steel [79]. One notable study revealed that buildings constructed using recycled steel generated 30% less waste and emitted 35% less CO_2 over their life cycle. Furthermore, renewable materials such as wood and cork have been shown to make significant contributions to resource conservation, as these materials can regenerate faster than their rate of consumption [80].

As illustrated in Figure 6, environmental benefits account for the largest share (45%) among the key aspects considered in the evaluation of sustainable building materials. This indicates that reducing environmental impacts—such as greenhouse gas emissions and resource depletion—remains the most critical driver for the adoption of these materials. In comparison, economic advantages represent 25% of the total, highlighting the growing recognition of cost savings, energy efficiency, and long-term value in sustainable construction practices.

Another key environmental advantage of sustainable materials is their energy efficiency, particularly during the production and end-of-life phases. Materials that require less energy for manufacturing, transportation, and recycling such as locally sourced timber contribute to a substantial reduction in the overall carbon footprint of buildings [79].

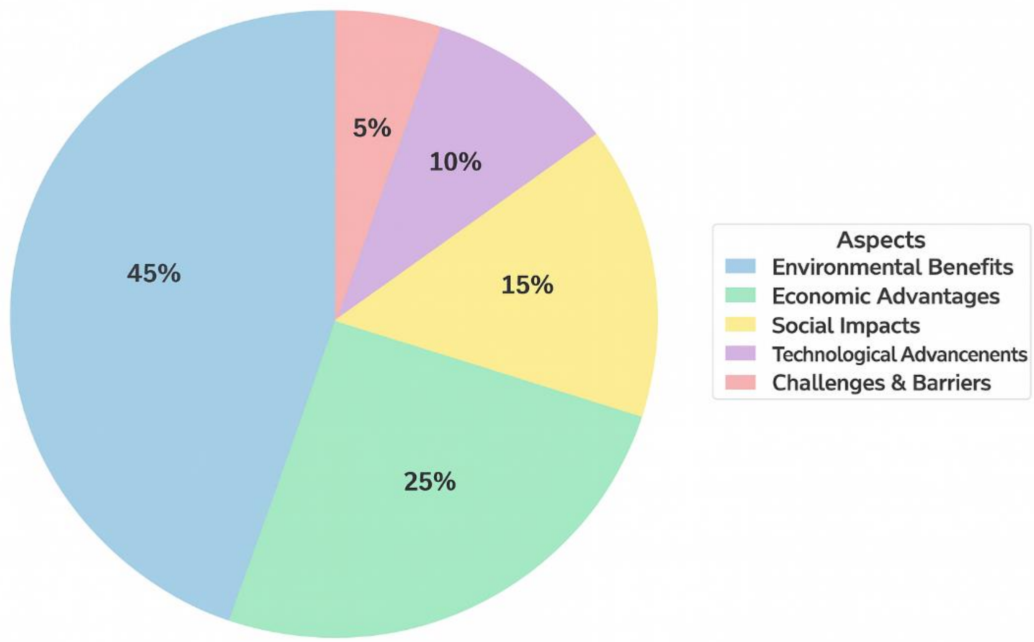


Figure 6. Key Impacts of Sustainable Materials on Building Design [80]

Social impacts constitute 15% of the considerations, emphasizing how sustainable materials contribute to occupant well-being and public health. Technological advancements (10%) and challenges & barriers (5%) are also acknowledged, reflecting the necessity for innovation and policy support to address limitations in adoption.

There is substantial evidence supporting the environmental, economic, and social benefits of using sustainable materials in building design and construction. These materials play a critical role in reducing greenhouse gas emissions, conserving natural resources, and enhancing the health and well-being of building occupants [81].

However, factors such as cost, accessibility, and structural performance pose significant barriers to their widespread adoption.

The data suggest that while environmental and economic gains are well recognized, overcoming the remaining challenges represented by the smallest portion in Figure 6 requires coordinated efforts through technological innovation, regulatory frameworks, and increased stakeholder awareness.

8. Conclusion

The use of sustainable materials in building design and construction provides significant environmental, economic, and social benefits. The findings confirm that materials such as recycled steel, bamboo, and low-carbon concrete can substantially reduce greenhouse gas emissions and contribute to the conservation of natural resources. Life Cycle Assessment (LCA) emerges as a critical tool for analyzing environmental impacts.

From an economic perspective, although the initial costs of sustainable materials may be higher, their long-term advantages include reduced operational expenses, energy savings, and lower maintenance requirements—making them cost-effective over time. Socially, the use of sustainable materials enhances indoor air quality, reduces health risks associated with toxic emissions, and improves the well-being of building occupants. Furthermore, the use of locally sourced materials supports community engagement and promotes local economic development.

However, challenges still remain—particularly in developing regions where issues such as cost and limited accessibility are more pronounced. To overcome these barriers, technological innovations, government incentives, and stronger legal and regulatory frameworks are of critical importance.

References

[1] H. Jaradat, B. Alhawari, K. Jreisat, M. Al-Tahat, and R. Al-Kilidar, "Green building, carbon emission, and environmental sustainability of construction industry in Jordan: Awareness, actions and barriers," Ain Shams Eng. J., vol. 15, no. 2, p. 102441, 2024.

[2] R. Kiani Mavi, H. Goh, C. Kang, and H. Lim, "Sustainability in construction projects: A systematic literature review," Sustainability, vol. 13, no. 4, p. 1932, 2021.

[3] Y. A. Abera, "Sustainable building materials: A comprehensive study on eco-friendly alternatives for construction," Compos. Adv. Mater., vol. 33, p. 26349833241255957, 2024.

[4] Y. Andersson-Sköld, M. Thorsson, J. Rayner, M. B. Lindberg, L. Janhäll, and S. C. Klemm, "An integrated method for assessing climate-related risks and adaptation alternatives in urban areas," Clim. Risk Manag., vol. 7, pp. 31–50, 2015.

[5] C. Li, L. Zhang, M. Zhu, and H. Wang, "Green production and green technology for sustainability: The mediating role of waste reduction and energy use," Heliyon, vol. 9, no. 12, 2023.

[6] J. Robinson, A. P. Singh, R. Banerjee, and A. K. Verma, "Sustainable and environmentally friendly energy materials," Mater. Today: Proc., vol. 69, pp. 494–498, 2022.

[7] L. Moratis and F. Melissen, "How do the sustainable development goals question rather than inform corporate sustainability?" Resour. Conserv. Recycl., vol. 141, pp. 253–254, 2018.

[8] F. S. Hafez, M. M. El-Aassar, and A. S. Khalil, "Energy efficiency in sustainable buildings: A systematic review with taxonomy, challenges, motivations, methodological aspects, recommendations, and pathways for future research," Energy Strateg. Rev., vol. 45, p. 101013, 2023.

[9] E. Calliari, S. B. Fernandes, J. Waters, L. Nalau, and F. Davide, "Building climate resilience through nature-based solutions in Europe: A review of enabling knowledge, finance and governance frameworks," Clim. Risk Manag., vol. 37, p. 100450, 2022.

[10] A. Koch, C. Begemann, K. DeFries, and J. E. F. Mahli, "Human impacts on the climate prior to the Industrial Revolution," in Routledge Handbook of Climate Change and Society, A. Dryzek, R. B. Norgaard, and D. Schlosberg, Eds. London, U.K.: Routledge, 2025, pp. 113–130.

[11] A. Tisserant, A. Pauliuk, R. Merciai, M. Schmidt, B. Frye-Cloete, and S. E. Wood, "Solid waste and the circular economy: A global analysis of waste treatment and waste footprints," J. Ind. Ecol., vol. 21, no. 3, pp. 628–640, 2017.

[12] A. Akande, P. Cabral, and S. Casteleyn, "Assessing the gap between technology and the environmental sustainability of European cities," Inf. Syst. Front., vol. 21, pp. 581–604, 2019.

[13] S. Aydın, An example of an analysis on the concept of sustainability, the green concept, and their local-global reflections from a communication perspective, M.A. thesis, Istanbul Univ., Inst. of Social Sciences, 2017.

[14] W. R. Black, "Sustainable transportation: A US perspective," J. Transp. Geogr., vol. 4, no. 3, pp. 151–159, 1996.

[15] A. Osso, T. Walsh, and D. Gottfried, Sustainable building technical manual: Green building design, construction and operations, Public Technology Inc., 1996.

[16] G. Tenikler, Coastal management for a sustainable future in the Gulf of Izmir, M.A. thesis, Dokuz Eylul Univ., Inst. of Social Sciences, 2001.

[17] E. A. Hoşkara, A strategic management model for sustainable construction appropriate to national conditions, Ph.D. dissertation, Istanbul Tech. Univ., Inst. of Sci. and Technol., 2007.

[18] A. P. M. Velenturf and P. Purnell, "Principles for a sustainable circular economy," Sustain. Prod. Consum., vol. 27, pp. 1437–1457, 2021.

[19] A. Malik, A. Dhir, S. Al-Faryan, and D. P. Kothari, "Industrial revolution and environmental sustainability: An analytical interpretation of research constituents in Industry 4.0," Int. J. Lean Six Sigma, vol. 15, no. 1, pp. 22–49, 2024.

[20] H. Nuissl and S. Siedentop, "Urbanisation and land use change," in Sustainable Land Management in a European Context: A Co-Design Approach, Cham, Switzerland: Springer, 2021, pp. 75–99.

[21] P. K. Nath and B. Behera, "A critical review of impact of and adaptation to climate change in developed and developing economies," Environ. Dev. Sustain., vol. 13, pp. 141–162, 2011.

[22] A. G. Olabi et al., "Renewable energy systems: Comparisons, challenges and barriers, sustainability indicators, and the contribution to UN sustainable development goals," Int. J. Thermofluids, vol. 20, p. 100498, 2023.

[23] A. Salamzadeh et al., "Sustainability-oriented innovation foresight in international new technology based firms," Sustainability, vol. 14, no. 20, p. 13501, 2022.

[24] W. Visser, Landmarks for sustainability: Events and initiatives that have changed our world, London, U.K.: Routledge, 2017.

[25] H. Y. Hürol, A study on social sustainability: The case of Doğanbey urban renewal project in Bursa, M.S. thesis, Middle East Tech. Univ., Inst. of Natural and Applied Sciences, 2014.

[26] A. J. C. Fernandes, R. G. Rodrigues, and J. J. Ferreira, "National innovation systems and sustainability: What is the role of the environmental dimension?," J. Clean. Prod., vol. 347, p. 131164, 2022.

[27] M. Elsawy and M. Youssef, "Economic sustainability: Meeting needs without compromising future generations," Int. J. Econ. Finance, vol. 15, no. 10, pp. 23–31, 2023.

[28] S. Das and O. B. Hazarika, "The social, political, and institutional context of sustainability: A study of Indian agriculture," in Sustainable Agriculture and the Environment, San Diego, CA, USA: Academic Press, 2023, pp. 439–453.

[29] A. E. Kristoffersen, C. P. L. Schultz, and A. Kamari, "A critical comparison of concepts and approaches to social sustainability in the construction industry," J. Build. Eng., vol. 91, p. 109530, 2024.

[30] W. Fei et al., "The critical role of the construction industry in achieving the sustainable development goals (SDGs): Delivering projects for the common good," Sustainability, vol. 13, no. 16, p. 9112, 2021.

[31] D. G., Sahlol, Elbeltagi, E., Elzoughiby, M., & Abd Elrahman, M. (2021). Sustainable building materials assessment and selection using system dynamics. Journal of Building Engineering, 35, 101978.

[32] S. Jenkin and M. P. Zari, Rethinking our built environments: Towards a sustainable future: A research document, Ministry for the Environment, 2009.

[33] S. Petkar, Environmental impact of construction materials and practices, Ph.D. dissertation, 2014.

[34] A. G. Olabi et al., "The role of green buildings in achieving the sustainable development goals," Int. J. Thermofluids, vol. 25, p. 101002, 2025.

[35] S. Yıldız, G. Ş. Güneş, and B. Alim, "Criteria in building material selection and the role of sustainability," Kent Akademisi, vol. 17, Sürdürülebilir İnsani Kalkınma ve Kent, pp. 334–354, 2024.

[36] Xuan, L., Ju, Z., Skonieczna, M., Zhou, P. K., & Huang, R. (2023). Nanoparticles-induced potential toxicity on human health: applications, toxicity mechanisms, and evaluation models. MedComm, 4(4), e327.

[37] Y. A. Hajam, R. Kumar, and A. Kumar, "Environmental waste management strategies and vermi transformation for sustainable development," Environ. Challenges, vol. 13, p. 100747, 2023.

[38] One Planet Network, "Natural-resource use and environmental impacts," One Planet Network. [Online]. Available: https://www.oneplanetnetwork.org/SDG-12/natural-resource-use-environmental-impacts. [Accessed: Jan. 1, 2022].

[39] D.-E. Jung, S.-B. Yang, and S.-R. Yang, "The effects of local food on carbon emissions: The case of the Republic of Korea," Sustainability, vol. 16, no. 9, p. 3614, 2024.

[40] L. A. Nicholson, "Integrating sustainable building design and construction principles into engineering technology and construction management curricula," Age, vol. 9, p. 1, 2004.

[41] P. Kocaman, Evaluation of Bims aggregates and Bims concrete products in terms of architecture and sustainability, M.A. thesis, Mimar Sinan Fine Arts Univ., Inst. of Sci. and Technol., 2009.

[42] U. A. Umar, M. F. Khamid, and H. Tukur, "Sustainable building material for green building construction, conservation and refurbishing," in Proc. MICRA Postgrad. Conf., Malaysia, Dec. 2012.

[43] Al-Reshaid, K., Kartam, N., Tewari, N., & Al-Bader, H. (2005). A project control process in pre-construction phases: focus on effective methodology. Engineering,

Construction and Architectural Management, 12(4), 351-372.

[44] M. M. Bilec, R. J. Ries, and H. S. Matthews, "Life-cycle assessment modeling of construction processes for buildings," J. Infrastruct. Syst., vol. 16, no. 3, pp. 199–205, 2010.

[45] S. Lee, H. E. Chang, and J. Lee, "Construction and demolition waste management and its impacts on the environment and human health: Moving forward sustainability enhancement," Sustain. Cities Soc., 2024, p. 105855.

[46] S. M. A. Baharetha, A model for selecting sustainable exterior wall building materials/products in hot, humid climate, Ph.D. dissertation, King Fahd Univ. of Petrol. and Minerals, 2013.

[47] U. Civan, Evaluation of smart buildings in terms of environmental sustainability, M.A. thesis, Istanbul Tech. Univ., Inst. of Sci. and Technol., 2006.

[48] Abdolmaleki, H., Ahmadi, Z., Hashemi, E., & Talebi, S. (2025). A review of the circular economy approach to the construction and demolition wood waste: A 4 R principle perspective. Cleaner Waste Systems, 100248.

[49] J. Wu, X. Ye, and H. Cui, "Recycled materials in construction: Trends, status, and future of research," Sustainability, vol. 17, no. 6, p. 2636, 2025.

[50] A. A. Firoozi, D. O. Oyejobi, and A. A. Firoozi, "Innovations in energy-efficient construction: Pioneering sustainable building practices," Clean. Eng. Technol., 2025, p. 100957.

[51] M. S. Jain, Water-efficient technologies to reduce water consumption in the Indian buildings, [Unpublished].

[52] C. Du Plessis, M. Irurah, and L. Scholes, Agenda 21 for Sustainable Construction in Developing Countries, CIB and CSIR-Boutek, 2001.

[53] E. Guidetti and M. Ferrara, "Embodied energy in existing buildings as a tool for sustainable intervention on urban heritage," Sustain. Cities Soc., vol. 88, p. 104284, 2023.

[54] M. K. Dixit, Embodied energy calculation: Method and guidelines for a building and its constituent materials, Ph.D. dissertation, 2013.

[55] S. Barbhuiya and B. B. Das, "Life cycle assessment of construction materials: Methodologies, applications and future directions for sustainable decision-making," Case Stud. Constr. Mater., vol. 19, p. e02326, 2023.

[56] X. Yang, H. Zhou, and J. Gao, "Enhancing renewable energy productivity and energy efficiency of energy projects: How does cost of capital influence?," Energy Strategy Rev., vol. 57, p. 101608, 2025.

[57] Q. Tran, A. Khlaifat, M. Alshurideh, and S. Al Kurdi, "Empirical examination of factors influencing the adoption of green building technologies: The perspective of construction developers in developing economies," Sustainability, vol. 12, no. 19, p. 8067, 2020.

[58] A. Milad, "Recycled and upcycled materials in contemporary architecture and civil engineering: Their applications, benefits, and challenges," Clean. Waste Syst., 2025, p. 100203.

[59] M. Majerník, P. Daneshjo, and J. Moravčík, "Environmental technological innovations and the sustainability of their development," Ecol. Eng. Environ. Technol., vol. 24, 2023.

[60] F. Althoey, A. Ahmed, and M. Haruna, "Advancements in low-carbon concrete as a construction material for the sustainable built environment," Dev. Built Environ., vol. 16, p. 100284, 2023.

[61] F. Alam, S. Subic, and H. Naser, "Identifying barriers to effective BIM adoption in the re-engineering of construction business practices in developing countries," [Unpublished], 2023.

[62] C. R. Rusnak, "Sustainable strategies for concrete infrastructure preservation: A comprehensive review and perspective," Infrastructures, vol. 10, no. 4, p. 99, 2025.

[63] A. A. Firoozi, S. H. H. Jafari, and M. R. Kavussi, "Emerging trends in sustainable building materials: Technological innovations, enhanced performance, and future directions," Results Eng., 2024, p. 103521.

[64] I. Gil-Ozoudeh et al., "Sustainable urban design: The role of green buildings in shaping resilient cities," Int. J. Appl. Res. Soc. Sci., vol. 5, no. 10, pp. 674–692, 2023.

[65] H. K. Mohajan, "Impacts of construction and demolition waste on environment: An overview," Stud. Soc. Sci. Humanit., vol. 4, no. 3, pp. 1–5, 2025.

[66] T. M. Pham, "Fibre-reinforced concrete: State-of-the-art-review on bridging mechanism, mechanical properties, durability, and eco-economic analysis," Case Stud. Constr. Mater., 2025, p. e04574.

[67] Tarek, S., Mansour, Y., Abdelmohsen, S., Kohail, M., & Assem, A. (2025). Evaluating the role of additive manufacturing in adobe brick enhancement: A comparative study. Ain Shams Engineering Journal, 16(3), 103298.

[68] M. Valenzuela et al., "Towards the development of performance-efficient compressed earth blocks from industrial and agro-industrial by-products," Renew. Sustain. Energy Rev., vol. 194, p. 114323, 2024.

[69] P. Dulal et al., "Engineering properties of cement-stabilized compressed earth bricks," J. Build. Eng., vol. 77, p. 107453, 2023.

[70] R. Surwade and M. A. Kamal, "Exploring the potential of Hydraform interlocking block as a building material for masonry construction," Am. J. Civ. Eng. Archit., vol. 11, no. 2, pp. 45–51, 2023.

[71] Abbas, S., Saleem, M. A., Kazmi, S. M., & Munir, M. J. (2017). Production of sustainable clay bricks using waste fly ash: Mechanical and durability properties. Journal of Building Engineering, 14, 7-14.

[72] H. Bedlivá and N. Isaacs, "Hempcrete–an environmentally friendly material?," Adv. Mater. Res., vol. 1041, pp. 83–86, 2014.

[73] M. Yadav and A. Mathur, "Bamboo as a sustainable material in the construction industry: An overview," Mater. Today: Proc., vol. 43, pp. 2872–2876, 2021.

[74] C. Sun et al., "Are straw bales better insulation materials for constructions? A review," Dev. Built Environ., vol. 15, p. 100209, 2023.

[75] F. de Andrade Salgado and F. de Andrade Silva, "Recycled aggregates from construction and demolition waste towards an application on structural concrete: A review," J. Build. Eng., vol. 52, p. 104452, 2022.

[76] Evode, N., Qamar, S. A., Bilal, M., Barceló, D., & Iqbal, H. M. (2021). Plastic waste and its management strategies for environmental sustainability. Case studies in chemical and environmental engineering, 4, 100142.

[77] A. Schieweck and M.-C. Bock, "Emissions from low-VOC and zero-VOC paints–Valuable alternatives to conventional formulations also for use in sensitive environments?," Build. Environ., vol. 85, pp. 243–252, 2015.

[78] R. Khargotra et al., "Experimental study of eco-friendly insulating materials for solar thermal collectors: A sustainable built environment," Results Eng., vol. 21, p. 101681, 2024.

[79] L. Chen, J. Wang, R. Xu, and T. Yang, "Conversion of waste into sustainable construction materials: A review of recent developments and prospects," Mater. Today Sustain., 2024, p. 100930.

[80] A. K. M. Yahia and M. Shahjalal, "Sustainable materials selection in building design and construction," Int. J. Sci. Eng., vol. 1, no. 4, pp. 10–62304, 2024.

[81] P. Ekins and D. Zenghelis, "The costs and benefits of environmental sustainability," Sustain. Sci., vol. 16, pp. 949–965, 2021.

Electronic Journal
e-ISSN: 2980-0048