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IntechOpen Series
Sustainable Development, Volume 34

Sustainable Built Environment for People and Society

Edited by Masa Noguchi

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Published in London, United Kingdom

Sustainable Built Environment for People and Society
http://dx.doi.org/10.5772/intechopen.1005731
Edited by Masa Noguchi

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First published in London, United Kingdom, 2025 by IntechOpen
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British Library Cataloguing-in-Publication Data
A catalogue record for this book is available from the British Library

Sustainable Built Environment for People and Society
Edited by Masa Noguchi
p. cm.

This title is part of the Sustainable Development Book Series, Volume 34
Topic: Urban Planning and Environmental Management
Series Editor: Usha Iyer-Raniga
Topic Editors: Rui Alexandre Castanho and Luís Loures

Print ISBN 978-1-83634-521-3
Online ISBN 978-1-83634-520-6
eBook (PDF) ISBN 978-1-83634-522-0
ISSN 2753-6580

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Aims and Scope of the Series

Transforming our World: the 2030 Agenda for Sustainable Development endorsed by United Nations and 193 Member States, came into effect on Jan 1, 2016, to guide decision making and actions to the year 2030 and beyond. Central to this Agenda are 17 Goals, 169 associated targets and over 230 indicators that are reviewed annually. The vision envisaged in the implementation of the SDGs is centered on the five Ps: People, Planet, Prosperity, Peace and Partnership. This call for renewed focused efforts ensure we have a safe and healthy planet for current and future generations.

This Series focuses on covering research and applied research involving the five Ps through the following topics:

1. Sustainable Economy and Fair Society that relates to SDG 1 on No Poverty, SDG 2 on Zero Hunger, SDG 8 on Decent Work and Economic Growth, SDG 10 on Reduced Inequalities, SDG 12 on Responsible Consumption and Production, and SDG 17 Partnership for the Goals

2. Health and Wellbeing focusing on SDG 3 on Good Health and Wellbeing and SDG 6 on Clean Water and Sanitation

3. Inclusivity and Social Equality involving SDG 4 on Quality Education, SDG 5 on Gender Equality, and SDG 16 on Peace, Justice and Strong Institutions

4. Climate Change and Environmental Sustainability comprising SDG 13 on Climate Action, SDG 14 on Life Below Water, and SDG 15 on Life on Land

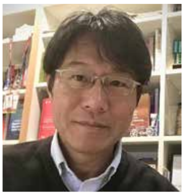
5. Urban Planning and Environmental Management embracing SDG 7 on Affordable Clean Energy, SDG 9 on Industry, Innovation and Infrastructure, and SDG 11 on Sustainable Cities and Communities.

The series also seeks to support the use of cross cutting SDGs, as many of the goals listed above, targets and indicators are all interconnected to impact our lives and the decisions we make on a daily basis, making them impossible to tie to a single topic.

Meet the Series Editor

Usha Iyer-Raniga is a professor in the School of Property and Construction Management at RMIT University. Usha co-leads the One Planet Network's Sustainable Buildings and Construction Programme (SBC), a United Nations 10 Year Framework of Programmes on Sustainable Consumption and Production (UN 10FYP SCP) aligned with Sustainable Development Goal 12. The work also directly impacts SDG 11 on Sustainable Cities and Communities. She completed her undergraduate degree as an architect before obtaining her Masters degree from Canada and her Doctorate in Australia. Usha has been a keynote speaker as well as an invited speaker at national and international conferences, seminars and workshops. Her teaching experience includes teaching in Asian countries. She has advised Austrade, APEC, national, state and local governments. She serves as a reviewer and a member of the scientific committee for national and international refereed journals and refereed conferences. She is on the editorial board for refereed journals and has worked on Special Issues. Usha has served and continues to serve on the Boards of several not-for-profit organisations and she has also served as panel judge for a number of awards including the Premiers Sustainability Award in Victoria and the International Green Gown Awards. Usha has published over 100 publications, including research and consulting reports. Her publications cover a wide range of scientific and technical research publications that include edited books, book chapters, refereed journals, refereed conference papers and reports for local, state and federal government clients. She has also produced podcasts for various organisations and participated in media interviews. She has received state, national and international funding worth over USD $25 million. Usha has been awarded the Quarterly Franklin Membership by London Journals Press (UK). Her biography has been included in the Marquis Who's Who in the World® 2018, 2016 (33rd Edition), along with approximately 55,000 of the most accomplished men and women from around the world, including luminaries as U.N. Secretary-General Ban Ki-moon. In 2017, Usha was awarded the Marquis Who's Who Lifetime Achiever Award.

Meet the Volume Editor



Dr. Masa Noguchi is an Associate Professor of Environmental Design at the Faculty of Architecture, Building, and Planning, University of Melbourne, specializing in Environmental Experience Design (EXD) to advance energy efficiency, affordability, and occupant wellbeing within the built environment. As the visionary leader of the ZEMCH Network, he spearheads global research and innovation in Zero Energy Mass Custom Homes (ZEMCH), driving sustainable housing development worldwide. A Chartered Engineer, Environmentalist, and Technological Product Designer, Dr. Noguchi possesses deep expertise in mass customization systems that deliver high-quality, affordable, and sustainable housing solutions. His groundbreaking work includes designing Canada's first near-net-zero energy modular home, the EcoTerra House, and leading transformative mass custom housing projects in Scotland and Brazil. Passionate about fostering interdisciplinary collaboration, he promotes knowledge exchange through international conferences, design workshops, and academic programs. Dr. Noguchi is dedicated to creating built environments that are socially inclusive, economically viable, environmentally responsible, and profoundly human-centric.

Contents

Preface

The needs and demands of the built environment are inherently fluid, shaped by evolving socio-demographic patterns, shifting human aspirations, and the escalating impacts of climate change. For instance, the growing prevalence of non-traditional household structures—such as single-person dwellings, multigenerational living, and shared housing models—has fundamentally reshaped how we approach housing design and performance. Promoting social sustainability requires moving beyond the conventional "one-size-fits-all" paradigm toward customizable and responsive living solutions. Flexibility and adaptability in design not only extend a dwelling's usability across life stages but also empower residents to inhabit spaces that reflect their changing needs, values, and identities. At the same time, the concept of affordability has expanded. It now encompasses not only the upfront cost of acquisition but also long-term operational expenses—particularly energy consumption. In an era marked by rising utility prices, deepening fuel poverty, and economic uncertainty, these ongoing costs are increasingly critical to housing accessibility and long-term viability. Genuine economic sustainability, therefore, must consider both construction affordability and lifecycle cost-efficiency to ensure that built environments remain livable and financially sustainable over time. The climate crisis further amplifies the environmental imperatives of the construction industry. As one of the major contributors to global greenhouse gas emissions, the built environment—especially the residential sector—must urgently decarbonize. With significant energy demands across both construction and occupancy phases, housing must move toward net-zero carbon—or ideally zero-energy—design principles that account for emissions across the entire building lifecycle, from material extraction to construction, use, and eventual deconstruction. This pursuit of sustainable built environments is a global imperative, underscored by the United Nations' Sustainable Development Goals (SDGs). Rapid urbanization, escalating climate risks, and widening socioeconomic disparities are placing unprecedented pressure on cities and communities worldwide. These intersecting challenges demand a paradigm shift in how we conceive, design, deliver, and manage built environments to foster resilience, inclusivity, and intergenerational sustainability.

This book explores research on sustainable built environments as a key to advancing several Sustainable Development Goals (SDGs)—particularly SDG 11 (Sustainable Cities and Communities), SDG 3 (Good Health and Well-being), SDG 7 (Affordable and Clean Energy), and SDG 13 (Climate Action). Achieving these interlinked goals requires an integrative approach that minimizes environmental impact, maximizes energy efficiency, and enhances quality of life—while remaining responsive to society's diverse and evolving needs. This calls for inclusive, adaptable, and resilient environments that proactively address dynamic social and ecological realities. It is within this complex landscape that the Zero Energy Mass Custom Home (ZEMCH) initiative was conceived. Established as a strategic response to global sustainability challenges, ZEMCH offers an innovative framework that integrates lean design and construction practices with mass customization strategies and renewable energy technologies. Its core mission is to deliver high-performance, affordable, and sustainable housing that meets individual lifestyle needs while addressing broader sustainability imperatives. By leveraging economies of scope—prioritizing diversity and flexibility over standardization—ZEMCH aligns cost efficiency with personalization, enabling the development of built environments that are low-carbon, energy-efficient, resilient, and human-centric. Since its inception in 2010, the ZEMCH Network has evolved into a dynamic global research and development ecosystem. Originating from the global vision of academic-industry collaborations on low- to zero-energy housing research and development, the network now connects more than 950 partners across nearly 45 countries. It fosters interdisciplinary collaboration through research partnerships, skill-building initiatives, and knowledge exchange. Regional centers in Australia, Brazil, India, Italy, Mexico, Peru, the Republic of Korea, the United Arab Emirates, the United Kingdom, and the United States support this mission by organizing flagship activities such as the ZEMCH Mission to Japan, international conferences, and hands-on design workshops—each serving as a conduit for innovation, policy engagement, and practical solution-building. Today, ZEMCH R&D knowledge is taught in academic programs globally.

Yet sustainable development is not solely about carbon reduction or construction efficiency. At its core, it is about cultivating built environments that promote human dignity, social inclusion, and environmental stewardship. Central to this vision is the principle of equity and accessibility—ensuring that all individuals, regardless of income, age, ability, or background, have access to safe, functional, and dignified living environments. Addressing this imperative is essential to mitigating systemic inequality and fostering cohesive, compassionate communities. Realizing this vision requires sustained and meaningful engagement with the people, these environments are meant to serve. Design solutions must be informed by the lived experiences and aspirations of diverse communities. Moreover, sustainability must be embedded across the entire building lifecycle—from planning and design to construction, operation, renovation, and eventual disassembly—ensuring that social, economic, environmental, and human objectives remain balanced at every stage. Ultimately, the realization of sustainable built environments depends on collaborative, multidisciplinary action. Architects, engineers, planners, policymakers, developers, and residents must work together to create innovative, practical, and inclusive housing solutions. This book aims to exemplify this collective endeavor, offering a scalable, locally adaptable model for sustainable built environments that respond to the urgent needs of our time and the aspirations of future generations.

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Section 1

Sustainable Living and the Built Environment

Chapter 1

Exploring Climate, Energy, and Environmental Justice in Climate Change, SDGs, and Transition Contexts

Lefteris Topaloglou and Konstantinia Nikolaidou

Abstract

The global and local debate on a sustainable and just transition to a low- or zero-carbon future inevitably involves the concepts of climate, energy, and environmental justice (CCE), which are largely interrelated. With reference to this broader context, this article explores the interplay of these three dimensions in relation to climate change, the sustainable development goals (SDGs), and the dynamics of the energy transition. The argumentation of the article is based on a critical and comparative analysis of the literature with the aim of preparing a holistic and inclusive analytical framework for addressing inequalities and a just and sustainable transition away from fossil fuels. By incorporating justice considerations into policy layout, worldwide agreements, and local practices, the context nurtures social resilience and sustainable development. The just transition concept surfaces as a critical enabler of equitable transformation, addressing labor force challenges, safeguarding energy access, and mitigating ecological destruction. By stimulating worldwide shared aims, participatory governance, and capacity building, this paper contributes to achieving justice in climate and energy transitions.

Keywords: climate justice, environmental justice, energy justice, just transition, sustainability

1. Introduction

The global need for a robust policy response to the challenge of climate change is linked to the urgent requirement for multi-level measures to deliver equitable and sustainable solutions for the entire global population. Addressing disparities in vulnerability of different regions of the planet requires tackling inequalities in access to energy resources, technology, and knowledge between developed and developing countries [1, 2].

Historically, it is self-evident that the industrialization of developed countries, driven by carbon-intensive industries, has been the largest contributor to greenhouse gas emissions. Meanwhile, developing countries disproportionately face the impacts of climate change in the form of environmental degradation, forced migration, and severe income losses [2]. These inequalities highlight the urgent need for a global approach that will ensure fair and sustainable development and the building of resilient and inclusive growth models.

A significant portion of the global population lacks access to basic energy services while affordable energy remains provocatively unequal [3]. As a result, unsustainable policies and practices further damage the environment and make ensuring a just and sustainable, inclusive transition extremely critical.

This article seeks to explore the extent to which an analytical framework of climate, energy, and environmental justice (CEE) can be related to frameworks addressing climate change, the sustainable development goals (SDGs), and the energy transition, to effectively tackle inequalities. The present research aspires to contribute to bridging the different approaches through a holistic and applicable framework of analysis toward policies related to equitable and sustainable development.

The paper is structured as follows. The first section outlines and synthesizes the challenges related to climate, energy, and environmental justice. The second section examines the interplay between CEE and climate change, the SDGs, and the energy transition. The fourth section offers a synthesis and discussion on the findings of the previous analysis. The last section presents the conclusions, policy recommendations, and directions for future research.

2. The challenge of CEE justice

2.1 Methodology and results

The research methodology that was adopted for the scope of the analysis of the critical factors, key challenges, different justice intersections, and perspectives was a comprehensive literature review. Aiming at a holistic analysis of these issues in relation to inequalities, this approach allows the identification of critical parameters, different approaches, and overlaps in the scientific debate. The analysis is further enriched by examining theoretical frameworks, policy documents, and case studies to ensure the necessary depth and scope for addressing challenges and solutions within the proposed holistic framework for justice and sustainability [4]. Through this approach, the article aims to deepen understanding of the interactions between climate, energy, and environmental justice.

The approach followed for this review was systematically organized into three different yet interlinked stages as illustrated in **Figure 1**: (1) the careful selection and critical evaluation of the studies; (2) a thorough content analysis of the key elements found in the articles selected; and (3) a comprehensive description and interpretation of the results which emerged from our analysis.

Additionally, aiming to identify the research dynamics in terms of scientific publications number among different intersections of justice, we used Scopus database for a systematic review, based on the following search criteria. First, we filtered the domains 'climate justice', energy justice', and 'environmental justice'. Second, we selected only peer-reviewed scientific articles published in journals and books, written in English. Third, the subject areas concerned 'social sciences', environmental sciences', energy', and 'engineering'. Fourth, we filtered the results using a year range from 2015 until 2025, since 2015, the 2030 Agenda for Sustainable Development was adopted.

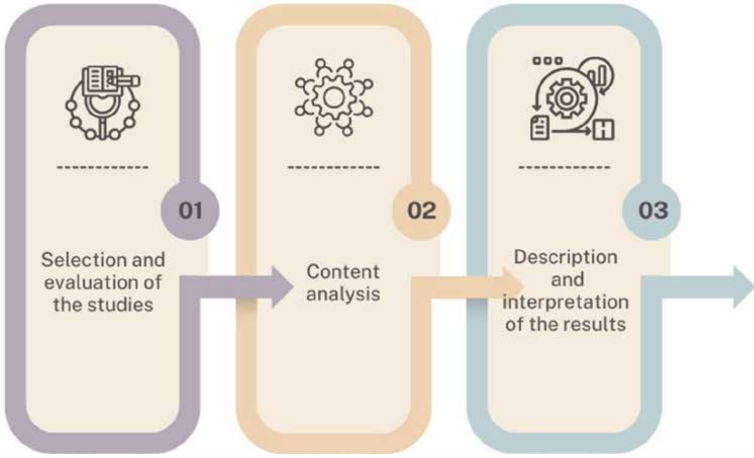

Figure 1.
Literature review steps. Source: Own elaboration.

Justice type	Number of articles	Percentage
Climate justice	5364	29.60%
Energy justice	2462	13.58%
Environmental justice	10,298	56.82%

Source: Own elaboration.

Table 1.
Systematic review on scopus database.

The results in **Table 1** indicate that environmental justice (56.82%) represents the most intensive researched area, probably due to the early recognition of environmental concerns across many disciplines. Climate justice (29.60%), although a relatively recent field of scientific engagement, seems to be exhibiting notable growth driven by the urgent need to address global inequalities associated with climate change. Energy justice (13.58%), while less widespread, seems to reflect a rapidly developing field of research to the extent that energy transitions have become imperatively included within the scientific research agenda indicating that there is significant potential for further research development in this area. One possible interpretation of this outcome is the fact that the notion of energy justice is relatively recent in comparison with the other two concepts [5].

2.2 Climate justice

Climate justice places particular emphasis on addressing the disproportionate risks, impacts, and responsibility of climate change among vulnerable populations in developing countries. This analysis assumes that developed countries, which are primarily responsible for greenhouse gas emissions, ultimately face fewer consequences compared to developing countries, which are more vulnerable. In other words, climate justice mainly examines how the risks and responsibilities of climate change are distributed [1, 6–8].

A notable concept in this context is that of 'double inequality' which highlights the reversal of the assignment of risk and responsibility. Developed countries, despite bearing the greatest responsibility, ultimately appear to be facing relatively mild consequences from the ongoing climate crisis. In contrast, less developed countries face serious risks to securing their essential resources, livelihoods, and overall security [1].

Addressing these stark inequalities in the global system requires generous funding from developed countries for the effective adaptation of vulnerable populations in developing countries to the persistent and pressing demands of climate change. The paradox lies in the fact that while the Global North is most responsible for the harmful consequences of climate change, it is ultimately the region of the planet that faces the least severe impacts. Global South, on the other hand, which also bears the lowest share of responsibility, is the one that suffers the most painful consequences in terms of its well-being, income, and security [2, 9, 10].

The literature highlights several key challenges in achieving climate justice. First, the impacts that developing countries face in terms of food security, livelihood risks, and increasing extreme weather events are disproportionate when compared to the corresponding data in developed countries [11]. Second, vulnerable populations rarely have access to the financial, technological, knowledge, or institutional resources essential for climate change mitigation strategy [12]. Third, international climate policies addressing the needs of marginalized vulnerable communities have so far focused more on generalized and vague solutions over targeted interventions that directly address specific needs of these vulnerable groups [13].

To address the aforementioned challenges, literature suggests several perspectives and pathways. First, the necessity of robust funding for climate change adaptation by prioritizing and specializing financial mechanisms at the international, national, and local levels, to support vulnerable populations and implement climate resilient strategies [1, 14]. Second, a focus on developing capacities, skills, and participatory approaches, through the transfer of necessary know-how and technical assistance tailored to the needs of vulnerable communities [15]. Third, the elaboration of cohesion policies that will ensure climate justice in a broader development and environmental context, through holistic and inclusive approaches [2]. Fourth, forging global solidarity by strengthening international cooperation and aligning adaptation efforts with climate justice principles of responsibility and risk sharing [6].

2.3 Energy justice

Energy justice focuses on the fair distribution of energy resources and equitable access to benefits for all. In the context of the energy transition in particular, major inequalities and challenges arise in terms of access, affordability, and sustainability of energy systems. Issues of energy poverty in particular highlight systemic inequalities that extend beyond the context of climate change. Addressing these inequalities necessitates the adoption of energy equity practices and sustainable approaches [3, 16].

Energy justice, alongside climate justice, are key elements in addressing vulnerability and fragility [16, 17]. Energy justice does not primarily center on communities affected by climate change. It focuses on the sectors and areas in which communities face these challenges, such as the affordability of energy goods [3, 16, 17]. Such approaches have steered research on issues of energy poverty [18], fuel poverty [19], and energy vulnerability [3, 20]. It is also emphasized that injustices and vulnerabilities are embedded within the energy transition itself and are not limited to the climate change process [10].

The literature review identifies several foremost challenges regarding energy justice. First, billions of people around the world tend to be marginalized, as they do not have access to affordable energy goods, reflecting a disproportionate burden of the energy transition on low-income communities [3, 21]. Second, rising energy costs disproportionately burden the financial resources of vulnerable households, making their access to basic energy goods problematic [22]. Third, the rapid expansion of investments in renewable energy sources has resulted in local tensions that take the form of land conflicts or even the displacement of entire communities [23].

Fourth, the transition from fossil fuels to clean energy disproportionately affects the workforce in traditional energy sectors, bringing to the fore the challenges of skilling, upskilling, and reskilling [22].

To address the challenges outlined above, several prospects and pathways can be highlighted. First, there is an urgent need for targeted investments of critical size and infrastructure development to ensure universal energy access that is affordable, especially in underserved areas and vulnerable communities [16, 23]. Second, to ensure a just transition of workers in the fossil fuel sectors, there is a need to design and implement comprehensive programs for retraining, social protection and employment incentives [24]. Third, renewable energy projects should primarily serve the needs and interests of local communities, through participatory initiatives, such as energy communities [25]. Fourth, sustainability strategies and policies should incorporate elements of energy justice and equity, addressing environmental, social, and economic challenges in a balanced manner [26].

2.4 Environmental justice

The focus of environmental justice analysis is primarily on the unequal distribution of environmental burdens and systemic inequalities that disproportionately affect vulnerable and marginalized communities. The roots of environmental justice lie in the environmental civil rights movements. Today, this spectrum has been extended to include issues related to race, socioeconomic status, disability, and global inequalities [5, 27].

Environmental justice emerged prominently in the 1960s, within the context of social transformation and activism movements. During this time, environmental justice advocates sought to highlight local environmental inequalities and link them to social, racial, ethnic, or socioeconomic factors [5]. Contemporary discourse has expanded the exploration of environmental inequalities that incorporates elements such as age, occupation, and physical disability, while also addressing inequalities that exist at a broader level, bridging both national and international gaps.

The literature review highlights a number of important challenges with reference to environmental justice. First, unequal exposure to risks. It is often observed that vulnerable and marginalized communities are those most exposed to environmental risks such as toxic waste, poor air quality, or industrial pollution [28, 29]. Second, the disproportionate degradation of natural resources due to overexploitation and land degradation, biodiversity harm, groundwater loss, and deforestation, respectively, cause disproportionate impacts on rural and indigenous populations [30]. Third, exclusion from decision-making centers causes a lack of representation of these affected communities, resulting in their inability to influence the formulation of environmental policies that take their needs into account [2]. Fourth, environmental degradation further exacerbates vulnerabilities and vulnerabilities to the impacts of climate change in extreme events such as floods, droughts, and heatwaves [31].

A number of perspectives and pathways are highlighted in literature to address the identified challenges. First, participatory governance has been shown to ensure the meaningful involvement of communities that have been excluded from decision-making processes at the local, national, and global levels [32]. Second, adopting an equitable approach to resource management through sustainable and equitable management practices that prioritize the needs of vulnerable populations can simultaneously protect ecosystems [2]. Third, through restorative justice, historical injustices can be addressed by drastically restoring the degraded environment and compensating affected communities [33]. Lastly, strengthening the legal arsenal by issuing strict environmental regulations and establishing mechanisms for fines and accountability can safeguard vulnerable populations [28].

2.5 Synthesis of challenges and pathways across justice domains

Table 2 attempts to capture a concise overview of the scientific debate related to climate, energy, and environmental justice, in relation to the main challenges, prospects, and pathway by category. Regarding climate justice, the disproportionate impacts on vulnerable populations are highlighted. Also, the importance of generous financing of climate change adaptation in the context of global solidarity and the need for investment in capacity building is underscored.

In the context of energy justice, it highlights issues such as energy poverty, the affordability of energy goods and services, and ensuring universal access to clean

Justice Domain	Major Challenges	Perspectives and Pathways
Climate Justice	Disproportionate impacts on vulnerable populations	Adaptation finance mechanisms [1, 14]
	Limited access to resources for adaptation and mitigation	Capacity building for community resilience [15]
	Global policy imbalances	Global solidarity and policy coherence [2, 6, 13]
Energy Justice	Energy poverty among marginalized communities	Universal clean energy access [16, 25]
	Affordability gaps	Just transitions for displaced workers [24]
	Sustainability trade-offs	Community-centered renewable projects [23, 25]
	Workforce transition challenges	Balancing sustainability goals with equity [22, 26]
Environmental Justice	Unequal exposure to environmental hazards	Participatory governance for inclusive decision-making [28, 32]
	Resource degradation	Equitable resource management practices [2, 30]
	Exclusion from policymaking processes	Restorative justice policies for affected communities [29, 33]
	Exacerbated climate vulnerabilities	Strengthening legal frameworks to ensure environmental accountability [28, 31]

Source: Own elaboration.

Table 2.
Summary of literature review in section 2.

energy. Additionally, it emphasizes the challenges of transitioning the workforce to green economy skills and the active involvement of the community and its needs in renewable energy projects. It also highlights the loss of jobs in fossil fuel industries, the emerging needs for new skills, and the importance of community engagement in renewable energy projects.

The issues around which environmental justice revolves include inequalities in exposure to environmental risks, exclusions from decision-making processes, disproportionate environmental remediation needs, and the necessity for a more robust legal arsenal to rectify injustices.

All these paths together could constitute a comprehensive framework for addressing inequalities in the direction of promoting just and sustainable energy transitions. The individual analysis of these distinct perspectives of justice intersects with issues that have common references to all three dimensions of justice, such as resource inequality, the risks of community exclusion from decision-making, and the disproportionate burden on vulnerable groups due to energy transitions and climate change. The above analysis attempts to introduce a holistic policy framework that integrates all three dimensions of climate, energy, and environmental justice toward strengthening the resilience of vulnerable groups, addressing inequalities and promoting equitable and sustainable development.

3. CEE justice within the climate change, SDGs, and just transition contexts

3.1 Methodology and results

The methodological approach in this section attempts to explore the interplay between three categories of justice (CEE) in relation to climate change, energy transition, and the sustainable development goals (SDGs) utilizing the Scopus database. The analysis seeks to identify trends, interactions, and thematic overlaps. The search criteria are consistent with those used in the previous section.

As illustrated in **Table 3**, in the context of climate change, climate justice appears to have a more prominent position (58,08%) in research. This finding emphasizes the need to address the unequal impacts of climate change, underscoring the necessity of a fair distribution of climate-related risks and responsibilities between developed and developing countries. Environmental justice from a research perspective also appears

	Climate justice	Energy justice	Environmental justice
Climate Change	3678	553	2102
	58,08%	8,73%	33,19%
Energy Transition	361	917	389
	21,66%	55,01%	23,34%
Sustainable Development Goals	238	160	396
	29,97%	20,15%	49,87%

Source: Own elaboration.

Table 3.
Interplay of CEE with climate change, SDGs, and energy transition.

to play an important role (33,19%) in protecting ecosystems and the environment. Energy justice, although appearing with the lowest research intensity (8,73%), highlights the need for equitable access to clean and affordable energy, in the context of climate adaptation and mitigation strategies.

From the energy transition perspective, energy justice appears to occupy the most prominent place (55,01%) in research activity, underlining the importance of equitable access to sustainable energy systems and the need to support areas affected by the shift away from fossil fuels. Research in this area often focuses on addressing the challenges of energy poverty, ensuring affordability and facilitating a smooth transition of the workforce. Climate justice intersects here with energy justice (21,66%), as the transition to cleaner energy systems seems to be necessary to achieve broader climate goals. At the same time, environmental justice (23,34%) emphasizes research challenges related to the environmental impacts of energy projects, such as land use conflicts and resource management in the perspective of sustainability and resilience.

When focusing on the sustainable development goals (SDGs), environmental justice stands out as the most important dimension (49,87%) in terms of research, reflecting the need to align environmental justice principles with goals of sustainable resource management, ecosystem protection, and social inclusion. This finding highlights the necessity to address systemic inequalities in the context of sustainable development. Climate justice, in turn (29,97%), aligns with the SDGs, particularly those focusing on reducing inequalities and promoting global cooperation. Energy justice (20,15%), although receiving less research attention, reflects the necessity of addressing energy poverty and ensuring resilient and inclusive energy systems within the context of the SDGs.

This integrated analysis reveals that while each justice dimension has its primary focus area, their interconnectedness is crucial for addressing the multifaceted challenges of sustainability. Together, they form a comprehensive framework that bridges social, environmental, and energy concerns, paving the way for equitable and inclusive solutions in the face of global transitions.

The above analysis, utilizing an integrated approach, highlights that while each dimension of justice focuses on different areas, their interconnectedness is crucial for tackling the multi-layered and complex challenges of sustainability. All these dimensions together could form a comprehensive analytical and interpretative framework that bridges social, environmental, and energy challenges.

3.2 CEE justice and climate change

Since the beginning of the 2000s, climate change has surfaced as a major concern for environmental justice due to its ties to human activities that produce greenhouse gas emissions, such as the burning of fossil fuels, along with actions that reduce the biosphere's capacity to absorb carbon dioxide, like deforestation [34]. Although climate change policies generally appear to be consistent with environmental justice goals, the strategies and specific measures taken may undermine environmental justice goals if they do not effectively address socioeconomic inequalities.

From an environmental justice perspective, climate change is a challenge that is expected to disproportionately affect vulnerable populations globally. These impacts are particularly severe in developing countries, which emit fewer greenhouse gases than richer countries. In this context, initiatives aimed at addressing climate change and at adaptation and mitigation strategies are considered to promote social and economic justice. However, a thorough examination of climate change measures, from the perspective of economists, social scientists, and political theorists, has shown that these measures may ultimately fail to address socioeconomic inequalities and may further exacerbate them [34].

The connection between climate change policies and climate, energy, and environmental justice passes through policies and measures to address the growing inequalities worldwide [34]. This interaction underscores the deep interdependence and the importance of coordinating policies at the global and local levels. The climate justice dimension emphasizes addressing the unequal impacts of climate change on less developed regions and vulnerable groups. These policies focus on measures to facilitate a smooth and just transition that will mitigate the impacts of climate change and protect marginalized social groups. In essence, what climate justice provides is a framework for the fair distribution of resources and responsibilities, supporting those most affected by the climate crisis [1, 2].

The energy justice dimension aligns with climate change to the extent that advocate policies that address energy-related inequalities, which affect the level of climate vulnerability of a region. Within this context, energy transition to renewable energy sources plays a pivotal role in mitigating climate change. However, this transition should ensure that energy-poor communities are not excluded. In this direction, energy justice focuses on equitable access to clean energy and on the sustainable energy transition of lower-income regions [3, 16].

Environmental justice complements climate justice to the extent that it incorporates the climate dimension of climate change. In this context, environmental policies include measures that enhance ecosystems that are key to climate resilience, while taking into account the needs of vulnerable and marginalized populations. In addition, environmental justice focuses on the active participation of groups most affected by the climate crisis in decision-making processes, giving them a voice [5, 34].

By integrating all these aspects of justice, policymakers will be able to develop holistic strategies to address the multifaceted challenges of climate change. Addressing inequalities and mitigating the impacts of climate change are essential for fostering sustainable and just outcomes at international, national, and local levels.

3.3 CEE justice and SDGs

The sustainable development goals (SDGs) address key universal challenges such as climate change and social inequality, providing a global framework for the specialization of policies at the national and regional levels. The three justice dimensions of the SDGs are highly correlated with the SDGs highlighting resource allocation, inclusivity and decision-making processes toward a just, sustainable and inclusive growth [17].

The global policy framework offered by the SDGs also encompasses the challenges of energy justice and environmental protection. Attempting to explore the interplay between the justice dimensions of the CEE and the SDGs, several significant insights are revealed.

Initially, climate justice seems to be closely linked with SDG 12 (climate action) which, while emphasizing climate change mitigation strategies, prioritizes vulnerable populations and inequalities. Climate justice also intersects with SDG 10 (reduced inequalities) by emphasizing equitable distribution of resources, global cooperation, and solidarity in terms of financing climate actions and the unequal impacts of climate change on excluded groups [2].

Energy justice is directly related to SDG 7 (affordable and clean energy) by advocating for fair and equitable access to sustainable energy resources. It also interacts with SDG 2 (no poverty) and SDG 11 (sustainable cities and communities) as it puts the challenge of energy poverty and urban resilience at the center of policies through a just transition to green energy [3].

Environmental justice intersects SDG 15 (life on land) and SDG 6 (clean water and sanitation) by underlining the need for fair and equitable access to natural resources for vulnerable populations. It also links with SDG 16 (peace, justice, and strong institutions) by promoting inclusive and participatory decision-making and all necessary institutional reforms that support environmental equity [5]. The integration of all these aspects of justice into the SDG policy framework is expected to contribute positively to sustainability while addressing systemic inequalities.

3.4 CEE justice and just transition

Since the Industrial Revolution, energy sources have undergone significant changes and transitions. The determinants of these changes have been cost, pollution, technological developments, and resource availability [35]. In the context of these developments, the idea of a just transition to a carbon-free economy is largely associated with the 'just process' that concerns society, the economy and the environment [10, 36].

However, the framework of just transition in a broad sense facilitates the integration of climate, energy, and environmental justice (CEE), providing a holistic framework and an interdisciplinary approach to address inequalities during the transition away from fossil fuels [10, 37].

The exploration of the interaction between each CEE justice dimension and just transition reveals some noteworthy insights.

The link between climate justice and just transition arises from the shared objectives of a fair distribution of resources and responsibilities in the decarbonization process. At the policy level, this means supporting vulnerable populations who have suffered the consequences of the climate crisis and who are most at risk. These policies encourage the transition and adaptation to a carbon-free future [1]. In other words, policies focus on measures that contribute to social equity through financing mechanisms for a smooth and just transition.

Energy justice aligns with just energy transition to the extent that it contributes to equitable access to and affordability of energy resources after the transition away from fossil fuels. In practice, this means supporting vulnerable low-income populations through initiatives that actively engage local populations in collaborative renewable energy investment schemes and fairly replace lost jobs. Examples of this interaction include retraining programs, employment incentives, and household subsidies for energy efficiency improvements [3].

Environmental justice seeks the equitable distribution of environmental burdens and benefits within the framework of a just transition, in a way that minimizes the impacts on vulnerable communities. Such policies include addressing ecological degradation and ensuring participation in environmental decision-making. In other words, environmental justice intersects with just transition to the extent that it encourages and supports the restoration of ecosystems affected by industrial and coal mining activities, enhancing ecological resilience [5].

Integrating the three dimensions of CEE justice potentially creates a comprehensive framework of inclusive transition policies and strategies that take into account all social, economic, and environmental dimensions of decarbonization, emphasizing that the transition toward sustainability necessitates a holistic approach.

4. Strengthening the conceptual link: Climate, energy, and environmental justice in the built environment

4.1 Intersections between climate, energy, and environmental justice in urban planning

Fair and sustainable urban development policies in relation to the built environment, to be effective, should be consistent with the principles of climate, energy, and environmental justice. This alignment is crucial to ensure that the energy transition does not exacerbate social, economic, and environmental inequalities and promotes an inclusive model of decision-making [3]. However, experience to date has shown that urban planning often overlooks inequalities in energy access and the degree of vulnerability to climate risks that exist within urban areas [38]. The integration of climate, energy, and environmental justice principles in urban planning is expected to contribute to the creation of an inclusive and sustainable urban environment for the benefit of all [39].

The fact that cities house around 50% of the world's population and consume almost 70% of the world's energy resources makes urban areas the epicenter of interest in the study of climate change vulnerabilities [11]. While cities benefit from economies of agglomeration due to the concentration of infrastructure and cost benefits, anti-agglomeration economies also occur due to environmental burdens and inequalities in energy access [3]. Insufficient urban infrastructure and inequal risk exposure among vulnerable groups further exacerbate energy poverty [38]. The principles of fair energy transition suggest that addressing these inequalities requires the integration of equity and sustainability into urban planning [39].

4.1.1 Climate justice in the built environment

Climate change impacts the population living in cities unevenly. Vulnerable populations with low-income and marginalized communities often bear the brunt of extreme climate change events due to their limited access to urban infrastructure against climate risks [40]. For this reason, urban planning should incorporate climate justice principles by emphasizing solutions that mitigate risks while enhancing environmental equity [41]. Emphasis should also be placed on initiatives to improve the energy efficiency of the building stock of vulnerable social groups [42]. In addition, many infrastructure investments aimed at bolstering climate change resilience infrastructure should prioritize deprived, low-income neighborhoods [38].

4.1.2 Energy justice and infrastructure

Equitable access to affordable, clean, and secure energy is one of the key foundations of equity in urban planning. Evidence, however, reveals an unequal spatial and economic distribution of urban energy infrastructure, renewable resources, and networks [43]. Vulnerable groups and low-income areas have degraded access compared to high-income groups and more centralized areas [17]. As a result, residents in these areas face higher energy costs due to the outdated and poor quality of buildings [44]. Additionally, instability in energy supply is frequently detected due to problematic networks in marginalized communities [38].

From the perspective of equitable energy policy, cities should emphasize local energy projects and decentralized energy systems that are able to reduce energy dependence on centralized grids and energy costs for vulnerable groups [45]. The challenge of low energy-efficient buildings requires well-designed investment policies for public buildings and social housing [46]. In addition, a favorable regulatory framework is required that can ensure affordable and seamless access to energy services [40].

4.1.3 Why these links matter for just energy transitions

Looking at the interaction between justice and urban space in relation to the energy transition, it is clear that this transition is not only about abandoning fossil fuels. In the urban built environment in particular, the energy transition to be equitable should incorporate policies of equitable and affordable access to all social groups [38].

Linking also urban design strategies to climate resilience priorities across the urban population could help mitigate climate risks especially for marginalized low-income groups. Examples of such design include green roofs, passive building design and permeable infrastructure [39]. Access to appropriate financial instruments is also crucial for mitigating the impacts of climate change [45].

Another important dimension is the development of an equitable energy governance framework. This practically means that all voices are heard and in decision-making processes no one is excluded [43]. Under such an approach, the most affected populations have access to policy formulation so that inequalities are not further widened [47].

In a sustainable urban development perspective, the extent to which the energy justice dimension is incorporated into planning not only enhances the decarbonization of fossil fuels but also strengthens the social cohesion and equity dimension [38].

Integrating the principles of equitable energy transition into the built environment in particular helps to enhance the sustainability and resilience of the urban environment. Numerus case studies of successful examples of equitable energy transitions in urban areas offer valuable insights and best practices regarding policy mechanisms [48].

4.2 Applications in urban planning and green building design

Equity and urban resilience strategies should integrate the built environment including infrastructure and building design [3]. Through this perspective, climate, energy, and environmental justice principles have an impact on the design of urban energy systems, the allocation of existing resources and fair access to sustainable systems [38]. Implementing these principles enhances the energy efficiency of buildings, the quality of urban services, and adaptation policies against climate change [39].

4.2.1 Decentralized energy systems for equitable access

There is no doubt that access to clean, affordable, and reliable energy is correlated with the characteristics of a city's energy infrastructure. Evidence suggests that when energy systems are centrally designed, social and economic inequalities widen within an urban system, in favor of wealthier urban centers and at the expense of economically weaker groups [38]. The shift toward small-scale energy investments enhances energy resilience and boosts energy democracy [43].

Decentralized energy systems help to address energy poverty better [40]. These systems enhance resilience against disruptions in areas that are vulnerable to extreme weather events [17]. Additionally, these types of decentralized energy investments empower local communities by reducing energy reliance on large energy companies [45].

A successful case: In Brooklyn, New York, the energy microgrid enables residents to exchange solar-generated energy, increasing energy resilience and reducing energy costs [43].

4.2.2 Energy-efficient, retrofitting, and affordable housing

A major challenge of a just energy transition in urban areas is to link energy efficiency with affordability. Retrofitting old buildings with a combination of better insulation and renewable energy sources can be instrumental in reducing household energy costs [49]. On the other hand, however, there is a risk of excessive rent increases due to energy upgrading of buildings resulting in the displacement of economically weaker populations [41].

Urban policies for upgrading building stock may include government subsidies and incentives to adopt energy efficient systems [44]. Regulations are also needed to prevent excessive rent increases to the benefit of tenants [50]. Social housing initiatives should also prioritize affordability and sustainability [46].

A successful case: The Vienna social housing model ensures access to low-income residents while incorporating modern energy efficiency systems [48].

4.2.3 Ensuring procedural justice in urban planning

The core principle of procedural justice at the urban setting ensures that all social groups have equal access to information, participation, and decision-making within a city [45]. However, evidence shows that in many large-scale urban regeneration projects, affected communities are left on the margins at risk of displacement, and resources are distributed unequally [51].

Improving the effectiveness of procedural justice requires participatory processes in urban planning that enable co-design approaches [52]. At the same time, local energy policies should generate immediate results and visible benefits to residents. A critical element in this perspective is the design of an inclusive local governance mechanism that ensures equitable allocation of resources and investments in urban infrastructure [45].

A successful case: The Superblocks initiative in Barcelona envisages active participation of residents in the design of the road network, in the provisions for pedestrian use of this infrastructure, in the design of urban green spaces, and in the planning of traffic within the city based on the principles of sustainability and viability [53].

5. Synthesis and discussion

Incorporating justice into the CEE framework enables a holistic approach to addressing the challenges of sustainable transition. This approach empowers policymakers to design just and effective policies that are aligned with the analytical framework of climate, energy, and environmental justice. This section delves deeper into the benefits that arise from a synthetic and integrated approach and analysis.

The multi-layered and complex challenges of sustainable transition, when intersected with the challenges of justice for climate, energy, and the environment, sharing common foundation the concepts of equity, inclusion, and systemic change. These common foundations and interconnectedness highlight the need to design integrated policies and holistic approaches to achieve sustainable and equitable outcomes.

A key insight from the above analysis is that climate, energy, and environmental inequalities is deeply intertwined. For instance, the disproportionate impacts of climate change on vulnerable groups and regions are linked to the goals of energy justice to reduce energy poverty and to ensure a fair distribution of resources and responsibilities within the framework of environmental justice. This interplay emphasizes the need to address climate, energy, and environmental challenges simultaneously and comprehensively within a policy framework that integrates the challenges of climate change, the SDGs, and just transitions.

Participatory governance, which ensures access and active participation of marginalized groups in decision-making, is particularly important in this context. This inclusive governance model applies to all dimensions of justice and all policy frameworks. Community-centered renewable energy investments are clearly aligned with energy justice goals by providing affordable access to energy goods. At the same time, they are aligned with environmental justice principles by reducing ecological damage and strengthening local resilience.

A prerequisite for the functionality of all these dimensions mentioned above is integrated planning at the policy level. This requires holistic frameworks that can integrate targeted climate action, the transition to green energy and the restoration of damaged ecosystems, re-skilling, and the social and economic protection of vulnerable communities.

A similar integrated approach model was successfully implemented in Germany, where the energy transition was aligned with social equity goals. Something similar was also attempted in Brazil, where ecosystem restoration projects were accompanied by participatory governance initiatives.

Table 4 provides a synthesis of the key insights analyzed in Sections 2 and 3, discussing the integrated pathways (climate change, SDGs, and just transition) against justice domain intersections and key challenges of justice.

Table 4 attempts to present an integrated approach to climate, energy, and environmental justice in relation to integrated pathways. For example, when considering the challenges of climate adaptation in relation to equitable access to energy and the protection of ecosystems, the need for cross-sectoral policy design emerges.

Similarly, tackling energy poverty, resource distribution inequalities, and the transition of the workforce to skills other than fossil fuels bring to the surface the magnitude of the risks of the transition through a multi-level analysis. It also emerges that these issues are interconnected and require coordinated actions and planning.

The elements presented in **Table 4** offer policymakers' valuable insight to design integrated strategies that simultaneously address the challenges of climate change, the SDGs, and just transition, while serving social, economic, and environmental goals.

The interlinkages of climate, energy, and environmental justice highlight the importance of close cooperation between international organizations, states, regions, and communities through models of multilevel and participatory governance.

In conclusion, this synthetic table aims to serve as a roadmap for a holistic approach and systemic change. By fostering integrated collaborative frameworks,

Integrated pathways	Justice domain intersections	Key challenges
Climate Change	Climate Justice and Energy Justice	Energy poverty exacerbated by climate vulnerabilities
	Climate Justice and Environmental Justice	Disproportionate climate impacts on marginalized groups and ecosystems
SDGs	Energy Justice and Environmental Justice	Land use conflicts and ecological degradation due to renewable energy projects
	Climate Justice, Energy Justice, and Environmental Justice	Inequities in resource allocation, decision-making exclusion, and implementation of sustainable transitions
Just Transition	Climate Justice and Energy Justice	Workforce transition challenges for fossil fuel-dependent communities
	Energy Justice and Environmental Justice	Ensuring economic inclusivity while minimizing ecological harm during transitions

Source: Own elaboration.

Table 4.
Synthesis of the key insights discussed in Sections 2 and 3.

policymakers could strengthen sustainability, justice, and resilience in both international and local contexts.

In conclusion, this synthesis table aims to serve as a roadmap for a holistic approach and systemic change. The information provided in **Table 4** constitutes the necessary elements that could be processed to formulate a holistic approach for systemic change. Within this outline, comprehensive policy frameworks could be designed with the aim of enhancing sustainability, equity, and resilience in both international and local contexts.

6. Conclusions

A holistic CEE justice framework is essential to effectively address the major challenges of climate resilience, equitable access to resources, and addressing inequalities. Within this framework, a just energy transition to a zero-emission economy, to be just, must ensure inclusiveness.

This necessitates embedding the principles of climate, energy, and environmental justice into policy design.

The analysis presented in this article demonstrates that while the dimensions of CEE justice are distinct and can be analyzed separately, they nevertheless have a strong interaction with each other as they share the common foundations of equality, inclusion, and systemic change. The extent to which climate, energy, and environmental justice frameworks are integrated into policies also determines the extent to which inequalities are effectively addressed.

Through the preceding analysis, it became clear that climate justice focuses on policies that aim to fairly adapt communities to the impacts of climate change. While energy justice focuses its attention on issues of access to energy goods and energy poverty, environmental justice in turn emphasizes protecting vulnerable communities from environmental risks and addressing inequalities in the management of natural resources.

The SDGs and the principles of just transition provide a useful roadmap for addressing the challenges mentioned above. A necessary condition in this direction is the alignment of initiatives at the global level with local needs. In this pathway, the dimensions of environmental justice complement and reinforce each other. For example, investments in renewable energy sources that actively involve communities simultaneously promote the goals of energy and environmental justice.

Acknowledgements

This research was supported by the European Union—Next Generation EU, National Recovery and Resilience Plan Greece 2.0, HFRI within the project 'JT-OBSERVATORY The impact of a Just Transition Observatory on energy transition. Exploring synergies with spatial justice and place-based governance through a comparative perspective'.

Conflict of interest

The authors declare no conflict of interest.

Thanks

The authors would like to express their sincere gratitude to the research team of ENTRA Lab (Laboratory of Energy Transition and Development Transformation) at the Department of Chemical Engineering, University of Western Macedonia, for their invaluable support and contributions throughout this study. Their expertise and dedication were instrumental in shaping the outcomes of this research.

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Chapter 2

Residential Energy Consumption in the Context of Energy Poverty: Socio-Technical Insights for Public Policy in Southern Chile's Cities

Alejandra Schueftan, Amapola Núñez, Eduardo Larrucea, Rafael Sanhueza and René Reyes

Abstract

This study examines residential energy consumption patterns in the city of Osorno, Chile. Through an interdisciplinary approach, it explores the use of energy modeling calibrated with socio-technical data gathered in the field. The aim is to contribute to the ongoing discussion on the design and implementation of thermal retrofitting policies while also offering valuable insights for decision-making in medium-sized cities. The results emphasize the importance of complementing theoretical energy consumption data with field-based information. In particular, the study reveals that energy consumption patterns in southern Chile are unique, characterized by widespread use of firewood in urban areas, energy constraints due to economic limitations, and high energy inefficiency in residential buildings.

Keywords: energy efficiency, energy poverty, air pollution, residential sector, public policies

1. Introduction

Approximately 2.7 billion people worldwide rely on solid biofuels, such as firewood, for various purposes, primarily heating and cooking. A significant proportion of this population is concentrated in the Global South [1]. In Latin America, around 19% of the population uses these fuels, while in various regions of Asia, usage ranges from 53 to 71%, reaching up to 82% in Africa [2].

This situation leads to high levels of air pollution from fine particulate matter (PM2.5), especially when environmental conditions are unfavorable. In Chile, seven of the ten most polluted cities in Latin America are located [3]. It is estimated that more than half of the national population resides in cities where air pollution exceeds the WHO's recommended thresholds [4], with adverse effects on both physical and mental health [5, 6] and significant public health and household costs [7].

In the central-southern cities of Chile, the climate is cold and humid, characterized by abundant precipitation throughout much of the year. To maintain adequate indoor temperatures, a significant amount of energy is required, most of which is met by wood-based fuels, particularly firewood and forest waste. In these cities, the residential sector contributes to over 90% of PM2.5 emissions, resulting in severe air pollution events in both urban and rural areas [8, 9].

The Environmental Decontamination Plan is the primary environmental management tool in Chile, aiming to reduce harmful atmospheric pollution and mitigate its effects. Its main measures include: (i) thermal retrofitting of houses to reduce energy consumption; (ii) replacement of heating systems with more efficient, lower-emission equipment; (iii) improvement and certification of the firewood; (iv) promotion of alternative heating methods such as pellets or electricity; (v) community environmental education and awareness; and (vi) stricter building standards for new houses [10]. These measures are developed and supervised by various ministries through sectoral programs.

Exposure to both indoor and outdoor pollution, poor housing conditions, and high household energy expenses contribute to high levels of energy poverty. Several studies recognize that the primary cause of energy poverty in central-southern Chile is inadequate or nonexistent insulation, compounded by inefficient heating systems and the fuels used for heating [11–13].

In this context, energy poverty is defined as the difficulty households face in meeting their energy needs while maintaining adequate thermal comfort [11, 12, 14]. Although it often overlaps with multidimensional poverty, energy poverty differs from income poverty [15] and affects a wide variety of households. According to the Energy Poverty Network (RED PE) [14], "a household is considered to be in energy poverty when it does not have equitable access to high-quality energy services to meet its fundamental needs, which are necessary for the human and economic development of its members." Thus, energy poverty is a social, transversal, and multidimensional phenomenon that varies geographically and is context-dependent [16].

A key consequence of energy poverty is that it exacerbates existing inequalities—material, health-related, educational, and social—associated with pre-existing poverty and creates further barriers to participation in society [17]. Certain households, neighborhoods, and cities are more vulnerable to energy poverty, facing greater difficulties in withstanding its long-term negative impacts [18]. For example, households with elderly members and/or children face energy needs that are twice the average, highlighting the demographic, socioeconomic, and physiological determinants of energy poverty, an issue addressed in this study.

Numerous studies suggest a close relationship between energy poverty and the energy efficiency of houses [12, 19–21], with much of this research being conducted in Europe. These studies demonstrate that physical housing characteristics, such as built area, orientation, type of insulation, and the efficiency of heating and cooling systems, significantly impact household energy consumption. Other studies have explored the influence of the surrounding environment, particularly urban form, and how it affects energy performance [22–24], showing that urban density, street orientation, and the presence of green spaces can influence residential energy consumption and, by extension, energy poverty levels.

To analyze the energy performance of houses, simulations using specialized software are commonly employed, requiring various types of data on the buildings' construction and user characteristics [25]. Studies on this subject often model individual buildings, gathering specific technical information, or model urban energy demand at a larger scale using statistical and micro-spatial analysis methods [26], with a focus on the relationship between housing typologies and energy consumption [27, 28].

Energy simulation models are important tools for studying the energy performance of houses [29, 30]. However, these models are based on a series of assumptions and simplifications that may not accurately reflect real conditions. Several studies suggest that the gap between model outputs and real behavior can be as high as 50% [31–33].

Both nationally and internationally, research in this area explores the potential correlations between user behavior and energy consumption, as well as the potential impacts of implementing thermal improvement measures [34, 35]. In this context, this study aims to address energy poverty from a socio-technical perspective and contribute to understanding the importance of calibrating theoretical energy consumption models with primary field data, allowing for more accurate and representative models [36–38].

In south-central Chile, theoretical energy consumption modeling has been studied in cities [39] and housing complexes [25], but these models have not been calibrated with socio-technical data collected on-site. This is due to the lack of centralized data on firewood consumption and the energy performance of houses, which would allow for the calibration and validation of model data.

Given the above, this study proposes the collection of typological (architectural and construction) characteristics of houses in a south-central Chilean city, along with on-site data gathering using methodologies such as household surveys, thermographic imaging, and interior temperature recordings. The goal is to assess socio-technical data and incorporate it into energy modeling to provide more accurate energy performance assessments. Furthermore, the objective of this study is to evaluate the implications of calibrating theoretical models with field data in order to assess their performance and potential for designing, prioritizing, and monitoring public policies aimed at improving energy efficiency in houses and addressing energy poverty. This approach could serve as a valuable decision-making tool for housing design and policy programs, considering diverse contexts, users, and future scenarios.

2. Case study

The Los Lagos region, located between 40°13′ and 44°03′ South latitude, is the area with the highest firewood consumption in Chile [40–42]. It borders the Los Ríos region to the north, the Aysén region to the south, Argentina to the east, and the Pacific Ocean to the west. In this region, 87% of urban dwellings and 99% of rural dwellings use firewood for heating [43]. This means that each household, both in urban and rural areas, relies on its own heating system, typically a wood stove or heater. The widespread use of firewood can largely be attributed to its lower cost and higher calorific value compared to alternative fuels, such as pellets, gas, or electricity [13]. Thus, low household incomes, high energy costs, and poor housing energy efficiency have driven the excessive use of firewood for heating in large urban areas.

This study focuses on Osorno, an intermediate-sized city in the Los Lagos region, which has exceeded health-damaging pollution levels since 2012. As a result, the first Environmental Decontamination Plan (PDA) was implemented in 2015 and updated in 2022. Osorno presents an interesting case study as it has been a pioneer in implementing these state-led decontamination plans. It is also in this region that Chile's first macrozonal Atmospheric Decontamination Plan is being implemented, which includes other municipalities such as San Pablo, Río Negro, Purranque, Puerto Octay, Frutillar, Llanquihue, Puerto Varas, and Puerto Montt.

This study focuses on the thermal retrofitting program, which is part of the PDA initiatives and is implemented through the Housing Thermal Conditioning Subsidy (DS 255) by the Ministry of Housing and Urban Development (MINVU). This subsidy provides co-financing for existing houses, up to 3905 USD, for thermal insulation of walls, roofs, and floors, control of air infiltration, sealing of doors and windows, ventilation mechanisms, and other measures. For households with elderly members and/or individuals with disabilities, a lower initial savings requirement is necessary. Additionally, households in the 60% most impoverished segment of the population can apply for an increased subsidy if the base subsidy is insufficient to fully improve the dwelling's thermal envelope.

Like other programs under the PDA, this one addresses specific aspects of energy poverty, but often without working in a coordinated manner. Additionally, the success of these measures depends on the beneficiaries' awareness and their ability to apply for subsidies, meeting specific technical and regulatory criteria for their houses. As a result, many households are unable to apply due to non-compliance with these technical or regulatory requirements, further complicated by uncertainty about the effectiveness of these improvements [44, 45]. Given the complexities involved in the execution of these measures, influenced by the specific conditions of the context in which the programs operate, this public policy offers an interesting opportunity for further study, exploring tools that can guide decision-making and enhance both its design and implementation.

3. Methodology

This study is part of the FONDEFIT21I0031 research project, titled "Model for Reducing Uncertainty Associated with Energy Efficiency Improvements at the Residential Level." An interdisciplinary methodology was applied, utilizing tools from architecture, engineering, geography, and social sciences.

To obtain comparable energy consumption scenarios, data was collected from both retrofitted and baseline (unmodified) houses. The retrofitted dwellings are those that received thermal improvements through the state subsidy from the Ministry of Housing and Urban Development (MINVU) between 2022 and 2023. Baseline houses, on the other hand, are those without any interventions and thus lack thermal standards, serving as the baseline or original dwellings.

Data gathered from various information collection methods was analyzed using multivariate techniques, examining the interactions between energy use, indoor comfort time, and household composition. Additionally, this data was used to model the energy performance of the dwellings using specialized software and incorporating the field-measured variables. In total, the study involved collecting data on housing typologies, conducting 198 household surveys with temperature and humidity measurements over 3 weeks, and capturing thermographic images of the same houses that were surveyed.

3.1 Housing typologies

Housing typologies were defined based on several criteria: number of floors, configuration, construction system, and year of construction. This resulted in three representative typologies (C, E, F). For each typology, base floor plans and elevations were developed, also considering sub-typologies that feature different facades but meet the same criteria for modeling energy consumption (see **Table 1**).

Typologies	Number of cases	Housing configuration	Sub-typologies		
			1	2	3
C	72 dwellings	Isolated 1 floor			
E	84 dwellings	Semi-detached 1 floor			
F	42 dwellings	Semi-detached 2 floors			

Source: Own elaboration for project FONDEFIT21I0031.

Table 1.
Housing typologies in the study.

The distribution of these typologies across the 198 studied houses is described below:

3.2 Survey application in households and temperature data collection

For the socio-technical characterization of the households, a survey consisting of approximately 50 questions was applied. The survey was divided into the following sections: general background, characteristics of the decision-maker, technical characteristics of the dwelling, multidimensional poverty, energy consumption patterns, and energy expenses.

The survey was applied randomly and proportionally to the relative size, resulting in a total sample of 198 houses randomly distributed across Osorno, consisting of 99 retrofitted houses and 99 baseline houses. The distribution of the sample can be seen in the following map (see **Figure 1**).

With the objective of measuring indoor temperatures in the houses, high-resolution iBUTTON Thermochron datalogger thermometers were installed, which have proven to be very effective for this purpose [46, 47]. The temperature and humidity were recorded every 30 minutes during the night (from 9:00 PM to 3:00 AM), hours when the heating is generally on and the residents are at home. Two thermometers were installed in each house: one in the room where the heating system was located and another in the coldest living space (not including bathrooms, kitchens, or storage rooms). These thermometers recorded temperature and humidity data every half hour for 3 weeks after installation and were installed and removed by the same people who conducted the surveys.

3.3 Thermographic image capture of walls

To capture thermographic images, a Fluke TiR32 infrared camera was used, designed specifically to detect surface temperature differences at both short and long

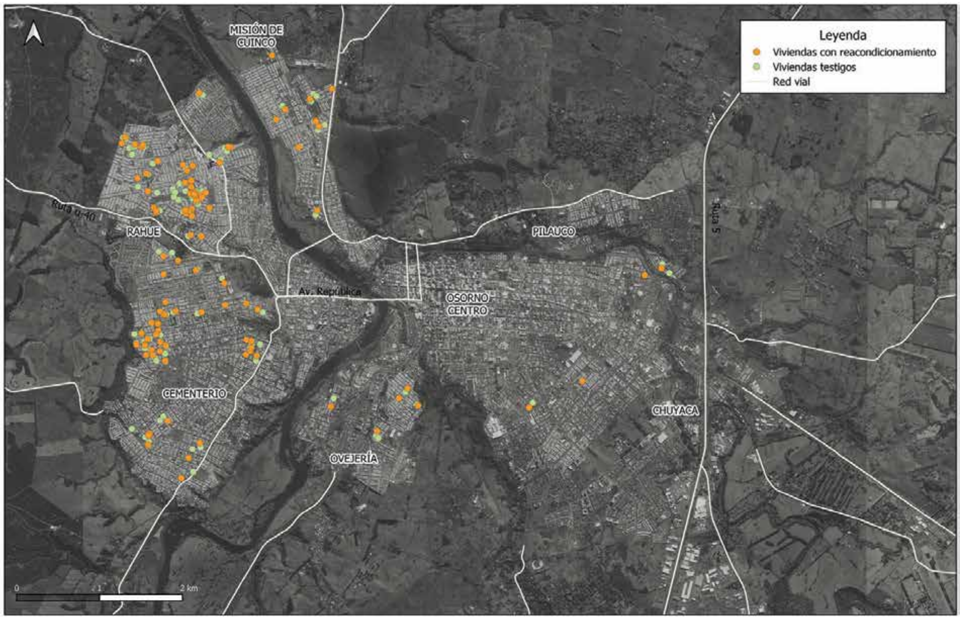

Figure 1.
Sample distribution in the city of Osorno. Source: Own elaboration for the project FONDEFIT21I0031.

distances. The images were captured at a maximum angle of 45 degrees to ensure maximum accuracy, ensuring there were no obstructions and achieving the best possible view at dusk when the sun was out. For each house, at least 6 images were taken to minimize errors and guarantee a comprehensive assessment. These images were analyzed using Smart View Classic 4.4 software to visualize each thermography and the temperature differences.

Once the thermographic images were processed, a synthesis sheet was created for each house, identifying key information for subsequent analysis. The thermography provides surface temperatures at each point or pixel of the image, so there will be as many U-values as there are pixels in the image. A weighted value of the surface (average) is then obtained as the U of the thermography, using Eq. (1) to determine U per pixel [48].

$$U = (5.8 + 3.8054\mu)(Tse - Te)/(Ti - Te) \quad (1)$$

Where:

- μ is the local wind speed in m/s.
- Tse is the superficial exterior temperature of the wall.
- Ti and Te are ambient interior and exterior temperatures.

3.4 Energy consumption modeling

In order to model scenarios that help understand the relevance of using field-obtained variables in software simulations, energy simulations were carried out to estimate heating consumption, considering different configurations of construction and architectural characteristics (typologies), housing orientation, and the presence of vulnerable populations in all their combinations (see **Table 2**). This is justified

	Theoretical scenario		**Calibrated theoretical scenario**	
	Baseline (2007 Standard)	**Retrofitted (PDA standard)**	**Baseline**	**Retrofitted**
With vulnerable population	The 3 typologies (C, E, F) with 3 inhabitants, usage hours: 18hours, temperature: 18°C, U-values according to 2007 standard.	The 3 typologies (C, E, F) with 3 inhabitants, usage hours: 18 hours, temperature: 18°C, U-values according to theoretical PDA.	The 3 typologies (C, E, F) with field data.	The 3 typologies (C, E, F) with field data.
Without vulnerable population	The 3 typologies (C, E, F) with 3 inhabitants, usage hours: 18 hours, temperature: 18°C, U-values according to 2007 standard.	The 3 typologies (C, E, F) with 3 inhabitants, usage hours: 18 hours, temperature: 18°C, U-values according to theoretical PDA.	The 3 typologies (C, E, F) with field data.	The 3 typologies (C, E, F) with field data.

Source: Own elaboration.

Table 2.
Modeled scenarios for housing and household characteristics.

Construction element	**Theoretical model**		**Calibrated theoretical model**	
	Baseline dwelling	**Retrofitted dwelling**	**Baseline dwelling**	**Retrofitted dwelling**
Wall thermal transmittance	U-value = 1.6 W/m^2°C, corresponding to the requirement of the OGUC Thermal Regulation starting from 2007. Although the houses were built before this regulation was applied, it has been established that around the year 2000, buildings already had a thermal standard similar to this regulation.	U-value = 0.38 W/m^2°C, corresponding to the requirement of the Osorno PDA (2022), applied to all thermal refurbishments carried out in that city.	The U-value = average of the thermographic measurements of the walls carried out in the field for the 99 reference houses.	The U-value = average of the thermographic measurements of the walls carried out in the field for the 99 refurbished houses.
Roof thermal transmittance	U-value = 0.33 W/m^2°C, corresponding to the requirement of the OGUC Thermal Regulation starting from 2007, which had already been applied by Chilean standards since the year 2000.	U-value = 0.32 W/m^2°C, corresponding to the requirement of the Osorno PDA (2022), applied to all thermal refurbishments carried out in that city.	U-value = 0.33 W/m^2°C, corresponding to the requirement of the OGUC Thermal Regulation starting from 2007, which had already been applied by Chilean standards since the year 2000.	U-value = 0.32 W/m^2°C, corresponding to the requirement of the Osorno PDA (2022), applied to all thermal refurbishments carried out in that city.

Construction element	**Theoretical model**		**Calibrated theoretical model**	
	Baseline dwelling	**Retrofitted dwelling**	**Baseline dwelling**	**Retrofitted dwelling**
Floor thermal transmittance	Since the floors of the houses were not intervened during the thermal retrofit process and all models have a ground-bearing slab floor directly on the ground, the heat loss was calculated for each model using the known formula for linear floor transmittance, Kl, as follows: $Q = K_1 * Per * \Delta t$ Where: • K_1 = 1.4 for traditional ground-bearing slab without insulation • Per = Perimeter of the house (m) With this calculated value, a U-value for the floor was determined as input for the software.			
Door thermal transmittance	The thermal transmittance value of a door varies depending on whether it is made of solid wood or a lightweight construction. Generally, a lightweight wood door is used, with an average U-value = 2.8 W/m^2°C. This value matches the requirement for thermal retrofit.			
Window thermal transmittance	U-value = 5.8 W/m^2°C, assuming the windows are single-glazed.	U-value = 3.6 W/m^2°C, which is the value for double-glazed windows required by the PDA (2022).	U-value = 5.8 W/m^2°C, assuming the windows are single-glazed.	U-value = 3.6 W/m^2°C, which is the value for double-glazed windows required by the PDA (2022).
Infiltrations (ACH)	The value applied is 23 ACH. This value was considered due to the type of housing with a light wooden structure and based on the baseline established in the "Manual of Air Tightness of Buildings" (2014). For this case, the manual specifies an average of 24.6 ACH with a standard deviation of 12.4 ACH (at a pressure level of 50 Pa). Since the reference houses had improved insulation for their data (2007 standard), a level of 23 ACH was considered for the modeling.	A value of 5 ACH (n50); this value is used as it is the requirement of the PDA (2022).	The value applied is 23 ACH. This value was considered due to the type of housing with a light wooden structure and based on the baseline established in the "Manual of Air Tightness of Buildings" (2014). For this case, the manual specifies an average of 24.6 ACH with a standard deviation of 12.4 ACH (at a pressure level of 50 Pa). Since the reference houses had improved insulation for their data (2007 standard), a level of 23 ACH was considered for the modeling.	Currently, there is no data on infiltration in retrofitted houses. However, some tests have been conducted in new light-structured houses with the Osorno PDA standard, with results around 8 ACH (n50). Nevertheless, for the models incorporating actual data from retrofitted houses, an estimated air change rate (ACH) of 12 was assumed, reflecting improvements in the thermal retrofit implementation. This estimation was based on the reduction values at specific locations within the house, considering areas that were sealed or improved, as outlined in the 'Manual of Air Tightness of Buildings' (2014).

Source: Own elaboration.

Table 3.
Thermal transmittance values and technical characteristics for each modeled scenario by construction element.

since, through the surveys, we confirmed that the presence or absence of vulnerable populations (children and/or elderly) directly influences energy usage patterns, which in turn determines the interior temperature of the house and the times when the household remains within thermal comfort ranges.

These simulations were conducted for houses that have not undergone any thermal upgrades (referred to as "baseline" houses) and for houses that have been upgraded through the state program implemented by the Ministry of Housing and Urbanism (MINVU) as part of the Air Pollution Control Plans (referred to as "retrofitted" houses) (see **Table 2**).

The technical and construction characteristics of the houses used for modeling each of the scenarios are described in **Table 3**.

The simulations were carried out using the DesignBuilder software integrated with EnergyPlus, which enabled precise modeling of the energy demand of the dwellings. The integration with EnergyPlus allows for the simulation of the houses' energy performance, evaluating variables such as heating demand and the behavior of construction materials under various climatic conditions.

4. Results

4.1 Socio-technical characterization and comfort conditions of households

Regarding the social characterization of the surveyed households, most of them belong to low-to-medium income groups (quintiles 1 and 2), are small households (up to 3 inhabitants), and have a high presence of vulnerable groups; over 50% of the cases include households with elderly people or children under 5 years old.

In terms of energy usage patterns for heating, the majority rely on firewood (83% of the households), followed by pellets (15%) and gas (12%). However, it is common for households to use more than one fuel type for heating, which is represented by the combined use of energy sources (**Figure 2**).

As can be observed, the transition to more modern energy sources, such as pellets or electricity, is not abrupt, and there is no complete replacement of fuels by households, with mixed energy sources being predominant. The fuels used without combinations are firewood (36%), gas (3%), and pellets (3%), while electricity is used in only 1% of the cases.

Regarding the comfort conditions of the households, it is observed that, in all cases, the houses that underwent thermal improvement spend more time within the thermal comfort range than the houses without improvements (at least 20% more),

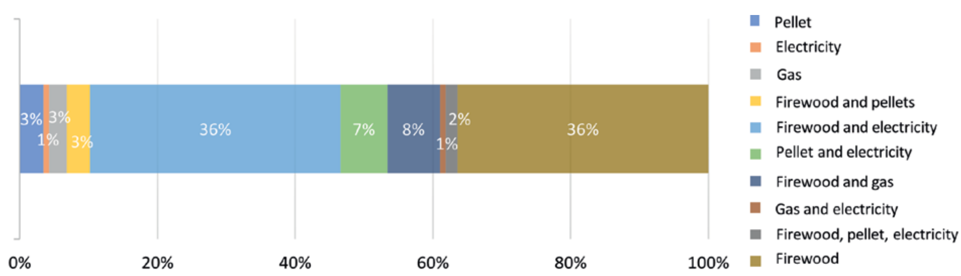

Figure 2.
Combined use of fuels for heating Source: Own elaboration.

	Energy efficiency interventions	Without vulnerable population	With vulnerable population
Energy consumption in winter (kWh)	Baseline	9.526	9.492
	Retrofitted	12.007	14.886
Average indoor temperature (°C)	Baseline	19.1 °C	20.4
	Retrofitted	17.7 °C	18.8
Percentage of time within thermal comfort range	Baseline	60%	70%
	Retrofitted	42%	57%

Source: Own elaboration.

Table 4.
Comparison of dwellings with or without thermal improvement and vulnerable population.

with indoor temperatures at least 2°C higher than the houses without any intervention or thermal upgrade (see **Table 4**).

Regarding comfort conditions, in households with vulnerable populations (elderly adults and/or children under 5 years old), a higher average indoor temperature and a higher percentage of time within thermal comfort were observed (see **Table 2**). It is estimated that the presence of these groups leads to higher energy consumption, as indicated in the survey, since they spend much of the day indoors and have needs to maintain healthy temperatures for longer periods.

Furthermore, it was observed that households that have carried out thermal improvements through state subsidies require less energy (kWh) to reach healthy temperatures and spend more time within the thermal comfort range. This highlights the positive impact of thermal retrofitting on general comfort conditions, including temperature, percentage of time within the comfort range, and energy consumption.

Additionally, through the survey, it was also confirmed that thermal retrofitting has an impact on the mental and physical health of residents. In retrofitted dwellings, there is a 30% reduction in health problems, a 20% reduction in sleep problems, and a 10% reduction in concentration issues associated with inadequate heating.

4.2 Energy modeling in different scenarios

Regarding energy modeling, the first significant result is that the theoretical model calibrated with field data has 26% more accuracy than the uncalibrated theoretical models (see **Table 5**). In other words, by incorporating variables such as the presence/absence of a vulnerable population, indoor temperatures, hours of heating usage, and thermal transmittance (U-values) of walls, the calibrated theoretical model more closely aligns with the energy consumption patterns reported by the households in the survey.

Upon closer examination of the results, both the theoretical and calibrated models tend to overestimate the energy consumption of the houses (see **Table 6**). In other words, the models predict a higher energy consumption than what is actually observed. This discrepancy can be attributed to the baseline condition of energy inefficiency in the houses and the energy poverty faced by the households, where the energy consumed is insufficient to reach the adaptive comfort temperature of 18.3°C. These findings suggest that households are unable to consume the necessary amount of energy to achieve adequate thermal comfort, indicating they are likely experiencing cold conditions during the winter months.

Typology	Theoretical model (kWh/m^2)	Calibrated theoretical model (kWh/m^2)	Surveys (kWh/m^2)	Diff. Theoretical model and survey (kWh/m^2)	Diff. Calibrated theoretical model and survey (kWh/m^2)	Adjustment of theoretical model to real consumption	Adjustment of calibrated model to real consumption
C	89	114	256	−166	−142	35%	45%
E	386	311	214	171	96	20%	55%
F	349	295	269	144	71	36%	68%
Average	274	231	225	50	6	30%	56%

Source: Own elaboration.

Table 5.
Energy simulations by housing typology.

Typology	Tipo	Vulnerable population (yes/no)	Theoretical model (kWh/m^2)	Calibrated theoretical (kWh/m^2)	Surveys (kWh/m^2)	Diff. Theoretical model and survey (kWh/m^2)	Diff. Calibrated model and survey (kWh/m^2)	Adjustment of theoretical model (%)	Adjustment of calibrated model (%)
C	Baseline	yes	109	130	311	−201	−181	35%	42%
		no	110	77	254	−144	−177	43%	30%
	Retrofitted	yes	69	140	249	−180	−108	28%	57%
		no	70	115	209	−140	−101	33%	52%
E	Baseline	yes	539	324	279	260	45	7%	84%
		no	542	219	212	330	8	−56%	96%
	Retrofitted	yes	235	280	187	47	93	75%	50%
		no	227	271	179	48	240	73%	−34%
F	Baseline	yes	486	347	242	244	106	1%	56%
		no	488	312	245	244	67	0%	73%
	Retrofitted	yes	148	400	173	−25	125	86%	28%
		no	272	298	161	111	−41	31%	75%

Source: Own elaboration.

Table 6.
Energy simulations in different scenarios.

	Adjustment of the theoretical model	Adjustment of the calibrated model
With vulnerable population	38%	53%
Without vulnerable population	21%	49%

Source: Own elaboration.

Table 7.
Model adjustment according to vulnerable population.

This trend is observed in all housing types, except for Type C, where both the theoretical and calibrated models tend to underestimate energy consumption. In other words, the theoretical model predicts lower energy consumption than what is actually observed. This discrepancy can be attributed to the less efficient design of this housing type, with a lower floor area-to-envelope ratio. However, the primary factor is likely the socioeconomic characteristics of the household, which require further study.

When comparing the energy consumption data of a retrofitted dwelling with a vulnerable population to one without a vulnerable population, such as dwelling C and dwelling F, it can be observed that the dwelling with higher thermal transmittance has lower energy consumption than the one with lower transmittance. This means that the consumption data appears to be inverted. However, by looking at the temperature data, it becomes clear that there is at least a two-degree difference between the dwellings with and without a vulnerable population. This shows that the dwelling with the higher temperature requires a greater energy input for consumption despite having lower thermal transmittance. Essentially, in order to raise the temperature by two degrees, a substantial amount of energy is needed over the course of the year, nearly 100 $kWh/m^2/year$.

In contrast, this pattern is not observed in the theoretical data, where the temperature is held constant across all models. In this case, it is evident that dwellings with higher thermal transmittance have higher energy consumption compared to those with lower transmittance. However, the difference can be attributed to infiltration, which is a highly variable and specific factor as it depends on the construction conditions of each house and could potentially lead to changes in energy consumption.

Furthermore, when observing the model adjustments according to the presence/absence of a vulnerable population, the calibrated model aligns more closely in cases where there is the presence of a vulnerable population (see **Table 7**). This can be explained because the calibrated model was set with energy consumption patterns from these households, which are specific to the comfort conditions, temperatures, and hours of use.

In this case, more precise data is available, and therefore, the model tends to align more closely with reality. Additionally, it is assumed that in houses without a vulnerable population, energy use patterns are more diverse; generally, they are small households that spend a large part of the day away from home, meaning they may have lower energy requirements, and that the model would overestimate energy consumption in these cases.

5. Discussion

Residential energy consumption encompasses various dimensions and complexities, some of which are addressed in this study. Globally, there is a trend toward the development of place-based policies that consider local factors. However, these policies often fail to address the individual user, who is the ultimate target of public policy, and the social and cultural complexities within their context [49]. Research suggests that contextual factors are critical drivers of energy transition processes and, therefore, have a direct impact on the implementation of public policies [50].

In this regard, it has become evident that more reliable and accurate data is needed to better estimate energy consumption patterns and their incidence on public policy. We observe that the thermal retrofitting implemented by the Ministry of Housing and Urban Development (MINVU) has a positive impact on households: it increases indoor temperatures, improves comfort levels, and reduces energy consumption. However, despite these advances, which have a significant individual impact on households, we note that the number of subsidies granted in 2022 only met 60% of the target set by the Atmospheric Decontamination Plan (PDA) [51]. This affects the overall expected outcomes of the policy, which aims to reduce critical air pollution levels in the city.

Additionally, this study reveals certain energy consumption patterns that are relevant for public policy. Households are consuming less energy than needed to achieve healthy temperatures, indicating that once thermal retrofitting is implemented, comfort levels will improve, but energy consumption may not decrease significantly. This is strongly influenced by the social characteristics of the households; when there is a presence of vulnerable populations, energy consumption is unlikely to decrease. This is a crucial finding for the preparation and design of public policies [52], as it allows for the adaptation of thermal retrofitting to diverse households through user profiles and for the development of models that identify these profiles across the city. This could enable the prioritization of areas most vulnerable to energy poverty and with a higher improvement potential, creating a multiscalar policy approach.

In this context, energy consumption modeling requires calibration with field data to more accurately estimate these patterns within an energy poverty context, where firewood use is widespread, households limit their energy use due to economic constraints, and dwellings with vulnerable populations have higher energy requirements. This aligns with previous studies [53, 54], which assert that the presence of vulnerable groups in a household correlates with higher energy needs as they have physiological requirements for energy services to heat their houses, live in larger dwellings, and spend more time indoors.

With these contextual complexities, which are common in intermediate cities in southern Chile, the calibrated model shows a 26% better fit, highlighting that the socio-technical characteristics of households (energy use patterns, presence of vulnerable groups, and thermal comfort) have a significant impact on the theoretical estimation of energy consumption, beyond the relevance of housing type and construction characteristics.

In this regard, the behavior of the calibrated model is consistent with previous studies suggesting that theoretical estimations need to integrate new variables, as they can either under- or overestimate the issue by up to 50% of the real energy consumption [36–38]. As observed in this study, in some cases, the difference can even be greater.

Nonetheless, the differences between both models and the actual energy consumption data remain significant. This can be explained by findings in various studies [50, 55], which argue that the energy behavior of households has a strong sociocultural, economic, political, and institutional component that is diverse and changes over time. This requires complementing the focus on individual households with a broader territorial or community-based approach.

Regarding the study's limitations, potential inaccuracies in the field data must be acknowledged, as the variable for actual household energy consumption was based on survey data, and since households purchase firewood gradually [11], they often lack precise records of their actual consumption. Furthermore, in estimating the thermal transmittance of the building envelope, only thermographic images of the walls were used. However, it is also necessary to have these values for the rest of the envelope. Additionally, there were no field tests conducted to assess airtightness, which could likely affect the calibration of the model.

Several challenges for future improvements in modeling have been identified. The primary complexity of these hybrid methodologies—calibrated models using field data—lies in their ability to be extrapolated to different contexts. This requires specialized tools and expertise to carry out the analysis. As a result, there is a need to develop simpler, more cost-effective methodologies while still relying on statistical models that account for the complexities of housing, households (users), and the sociocultural context. Such an approach would enable the analysis of neighborhoods and cities to improve public policy planning, design, implementation, and monitoring.

Acknowledgements

This research was funded by the National Research and Development Agency (ANID), through the project FONDEF IT21I0031 "Model to reduce uncertainty in residential energy efficiency improvements," Alejandra Schueftan acknowledges the support of Centro de Desarrollo Urbano Sustentable (CEDEUS), and the support of ANID BASAL FB210015 CENAMAD.

Conflict of interest

The authors declare no conflict of interest.

Notes/thanks/other declarations

We acknowledge the collaboration of Sofia Carrasco, a student in the Master's program in Sustainable Environmental Design (MADE) at Universidad Austral de Chile, for her assistance with data analysis, and Sofia Larrucea, a civil engineering student at Universidad Austral de Chile, for her support with the modeling work.

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Chapter 3

Human-Centered and Regenerative Design: Leveraging Biomaterials for Climate-Responsive Built Environment

Solano Thasnee, Chen Austin Miguel, Mack-Vergara Yazmín and Maria De Los Angeles Ortega Del Rosario

Abstract

As communities face growing pressures, such as rapid urbanization and climate change, transitioning to a regenerative built environment is crucial for a more sustainable and equitable future. Thus, this chapter explores strategies for a human-centered and regenerative built environment that addresses the challenges of urbanization, climate change, and societal needs through biomaterials. This approach focuses on creating housing and infrastructure that enhances people's quality of life while reducing environmental footprints, prioritizing sustainability, resilience, and adaptability to changing climate conditions. Key considerations include indoor air quality, thermal comfort, and built environment restoration. Regenerative design principles focus on systems that restore and regenerate natural ecosystems. Emerging innovations, biomaterials, and circular economy concepts are fundamental in implementing these principles. By using renewable resources and reducing waste, buildings and infrastructures can contribute positively to the environment rather than depleting it. Finally, case studies will illustrate how these strategies impact health, sustainability, and resilience.

Keywords: biomaterials, built environment, human-centered, regenerative design, sustainability

1. Introduction

Urbanization refers to the proportion of a population residing in urban areas, driven by rural-to-urban migration and/or population growth in cities. Rural areas, in contrast, are characterized by low population density, expansive open spaces, and economies reliant on agriculture, forestry, and natural resources. These areas often face limited infrastructure and access to essential healthcare, education, and transportation services. Conversely, urban areas with densely populated regions of at least 50,000 individuals [1] and developed infrastructure, including buildings, roads, and public utilities, serve as centers of commerce and industry. They provide diverse job opportunities and higher living standards, key factors attracting migration. While distinctions between rural and urban areas typically focus on size, density, and economic activity, definitions vary across countries and institutions (**Figure 1**).

Urbanization is significantly reshaping global demographics, with over 4.6 billion people—more than half of the world's population—now living in urban areas. By 2050, nearly 70% of the global population is projected to reside in cities, highlighting significant regional disparities and the need for coordinated efforts to achieve sustainable urban development [3]. Rapid urbanization brings issues, including infrastructure demands, environmental sustainability, and social equity.

Climate change, often linked to urbanization, involves long-term shifts in global or regional climate patterns, primarily driven by human activities such as fossil fuel combustion, deforestation, and industrial processes. These activities generate substantial greenhouse gas (GHGs) emissions, like carbon dioxide (CO_2) and methane (CH_4), which intensify global warming and disrupt natural climate systems.

By 2024, the impacts of climate change had become increasingly evident, with global temperatures rising approximately 1.5°C above pre-industrial levels, nearing the critical threshold outlined in the Paris Agreement [4]. Extreme weather events, such as heatwaves, hurricanes, and floods, have increased in frequency and intensity, affecting ecosystems, economies, and communities. The Arctic is warming nearly four times faster than the global average, leading to unprecedented ice melting and rising sea levels. Millions face droughts and water scarcity, while biodiversity loss accelerates due to habitat destruction and ecosystem changes.

Despite these challenges, global efforts to combat climate change are gaining momentum. Many countries are implementing renewable energy initiatives [3, 5] and adopting circular economy strategies [3, 6, 7]. However, achieving net-zero emissions by mid-century requires more ambitious and coordinated global actions. Notably, cities and their residents, both major contributors to emissions and vulnerable to climate impacts, demand a comprehensive, human-centered approach to foster sustainable, resilient, and adaptive urban environments.

1.1 Need for transitioning to sustainable and regenerative built environments

A conventional built environment typically refers to buildings, infrastructure, and urban spaces developed with limited regard for environmental or social sustainability. It prioritizes economic gains, often relying on non-renewable resources, energy-intensive processes, and high-impact materials, leading to habitat destruction, pollution, and resource depletion [8, 9]. Additionally, it frequently neglects social well-being, creating inequitable, unhealthy spaces that degrade ecosystems, worsen climate change, and harm human health, making it unsustainable for long-term goals [10].

In contrast, a sustainably built environment prioritizes environmentally responsible, socially inclusive, and economically viable buildings and urban spaces [11]. Key features like energy and water efficiency, sustainable materials, and waste minimization reduce environmental impacts while fostering health, well-being, and accessibility. Sustainable designs integrate renewable energy, support biodiversity through green spaces, and enhance resilience to climate risks, creating balanced solutions that meet human needs while preserving resources for future generations.

However, merely achieving sustainability is no longer enough. Transitioning to regenerative built environments is essential to restore ecosystems, enhance biodiversity, and promote community well-being [12]. Regenerative design promotes positive

DOI: http://dx.doi.org/10.5772/intechopen.1009900

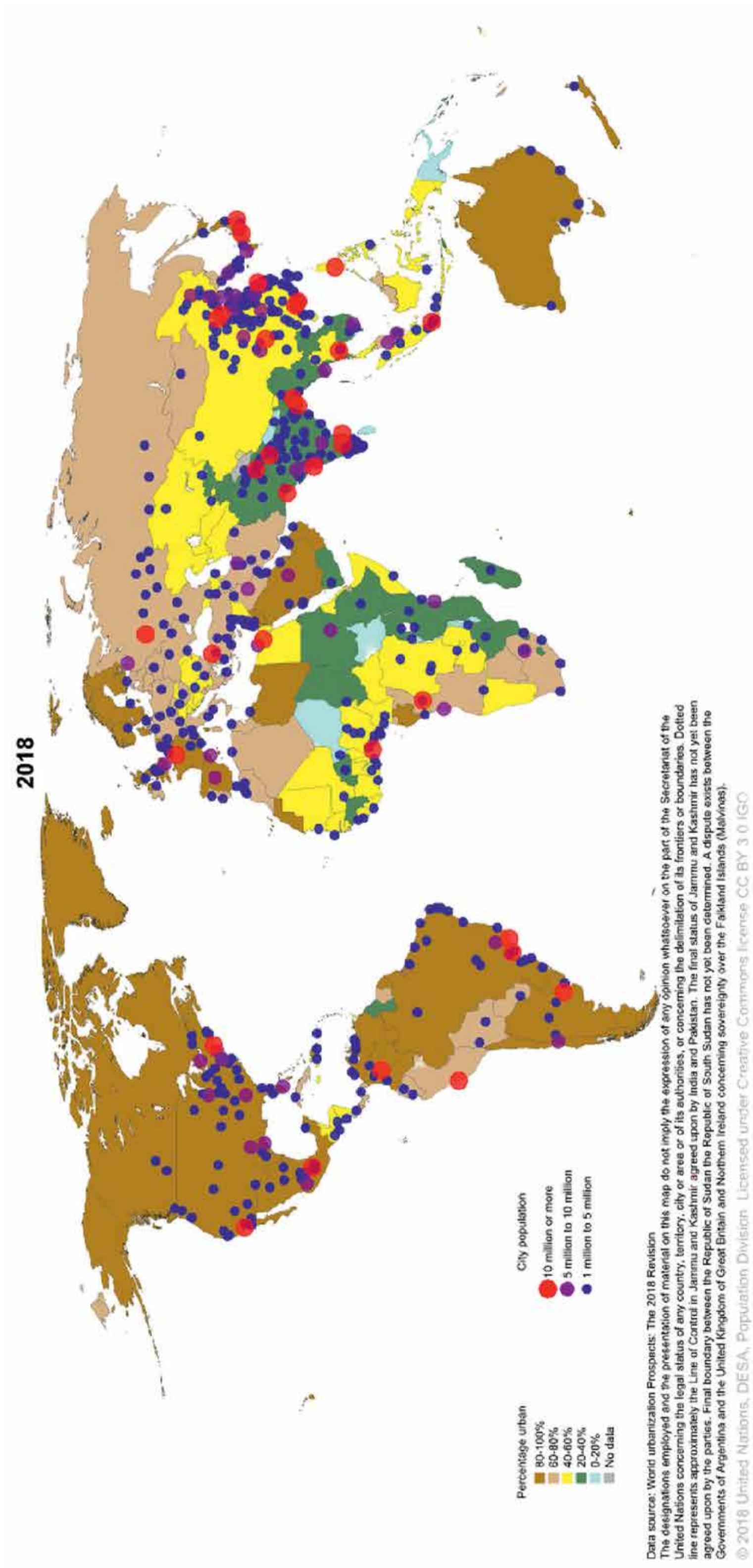

Figure 1.
Urban population percentages by country, sourced from the United Nations' World Urbanization Prospects: The 2018 Revision. Image reproduced from [2] under the CC BY-NC 4.0.

environmental impacts and resilience, fostering a harmonious relationship between human activities and nature.

This transition demands shifts in mindset, practices, and policies. Key steps include energy and resource efficiency through renewable energy, sustainable materials, and waste reduction, including green infrastructure, biodiversity-supporting designs, and water management systems. Collaboration among stakeholders ensures equitable, inclusive spaces, while regenerative practices focus on ecosystem restoration and achieving net-positive impacts. Policies, incentives for green practices, and education on regenerative principles are fundamental to this shift. Bio-based building materials are crucial in this transformation, offering sustainable, renewable alternatives that significantly reduce carbon footprints, potentially lowering costs and enhancing circularity [9, 13–17].

Thus, this chapter explores strategies for a human-centered and regenerative built environment that addresses the challenges of urbanization, climate change, and societal needs through biomaterials. Besides, case studies will illustrate how these strategies impact health, sustainability, and resilience.

2. Human-centered approach and biomaterials: Enhancing quality of life through design

When conceiving built environments, people-centered design prioritizes human needs, capabilities, and experiences. This approach aims to enhance adaptable spaces

Factor	Approach
Connection with natural elements	Natural light and windows: Exposure to natural light reduces depression and improves mood. Well-placed windows with an appropriate window-to-wall ratio (ideally 30%) enhance visual comfort and occupant satisfaction.
	Biophilic design: Integrating natural elements like vegetation and water into spaces fosters a connection with nature, improving emotional and mental well-being.
Comfort and environmental health	Indoor air quality (IAQ): Regenerative approaches go beyond reducing pollutants; they incorporate elements like air-purifying plants and technologies that optimize natural ventilation, reducing reliance on mechanical systems.
	Thermal comfort: Using passive strategies to maintain comfortable temperatures minimizes energy consumption and enhances physical well-being.
Lighting	Smart lighting systems and the proper color temperature (around 4000 K) are crucial for the perception of comfort and spaciousness. Additionally, optimal lighting levels (2000 lx) promote attention restoration.
Acoustics	Careful acoustic design, balancing privacy and connectivity, is essential in various environments, from offices to healthcare facilities.
Restorative spaces	Spaciousness: Ceiling height and large space dimensions reduce stress and promote comfort.
	Symmetrical layout and spatial alignment: Symmetry and alignment design promotes an esthetic and pleasant experience, increasing user satisfaction.
Visual stimuli	Visual complexity facilitates mental restoration through rich patterns and details, beneficially capturing involuntary attention.
Color and environment	Warm colors (orange, yellow) stimulate awareness, while cool tones (blue, green) help with concentration and reduce stress.

Table 1.
Key components of the human-centered approach based on the works of Pistore et al. [19, 20].

that respond to human behaviors rather than forcing individuals to conform to rigid environments. Its goal is to promote well-being, comfort, and interaction with their surroundings [18]. Unlike traditional paradigms that focus on functionality or isolated efficiency, human-centered design encourages the creation of holistic spaces by integrating factors such as natural light, air quality, acoustics, thermal comfort, and biophilic design. These factors ensure that built environments are functional but also restorative and harmonious [19, 20]. **Table 1** describes the approach to each key component.

The people-centered design, integrated into a regenerative approach, redefines built environments as functional, experiential, restorative, and connected to nature. This approach allows people to thrive physically, emotionally, and psychologically, fostering harmony between the built environment and its inhabitants [19, 21].

3. Regenerative design approach and biomaterials: Definition, principles, framework

3.1 Defining regenerative design

Regenerative design emerges as an integral response to the challenges posed by human settlements, which depend heavily on the resources, benefits, and services provided by ecosystems while simultaneously deteriorating their health and functionality [22]. This approach calls for higher organizational-level interventions, adopting holistic, transdisciplinary, adaptive, and eco-mimetic methodologies.

John Tillman Lyle introduced regenerative design as a framework for designing urban landscapes to restore degraded ecosystems. Over time, the concept has evolved, incorporating principles such as bioregionalism, permaculture, living systems thinking, and theories of human development and organizational design [23]. Regenesis articulates that regenerative design focuses on aligning human aspirations and activities with the evolution of natural systems, promoting co-evolution as a guiding principle for resilience and sustainability.

At its core, regenerative design seeks to restore and nurture the interdependent relationships between human and natural systems. This perspective enables conditions where all life forms can coevolve and thrive [24]. Moreover, as Caniglia et al. [25] noted, regenerative development reflects on the past and future possibilities to create systems that coevolve while generating shared prosperity on a healthy planet. In essence, regenerative design is a methodology that eases the co-evolution of anthropogenic and natural systems within a collaborative framework [26].

Developing regenerative thinking requires cultivating reflection and discernment while adhering to life-centered principles. It entails understanding life's dynamics and interconnected functions. In this context, Caniglia et al. [25] identify seven key principles—Whole, Potential, Essence, Development, Nested Wholes, Nodal, and Value-Adding Process Reciprocity—to address complex situations and generate innovative solutions, as outlined in **Table 2**.

3.2 Moving beyond sustainability to regenerative systems

The concept of sustainability has been key to conserving resources and mitigating human impact on the planet. Since its inception in the seventeenth century and its evolution into "contemporary sustainability," it has driven significant progress

Principle	Description	Practical application
Whole	Living systems must be understood as dynamic wholes interconnected with their environment.	Urban design that integrates ecological, social, and economic systems into a unified framework.
Potential	Discovering and fostering the unique potential of each system without imposing external standards.	Community projects that build on local strengths rather than applying generic models.
Essence	Recognizing the unique essence of each being or system beyond superficial classifications.	Architectural restoration that respects the historical and cultural identity of a place.
Development	Encouraging personal and organizational growth to fully express essence.	Training programs that promote critical thinking and systemic problem-solving skills.
Nested wholes	Systems are interconnected and operate as a web of interdependencies.	Regional planning that links local communities to global sustainability strategies.
Nodal	Identifying key points where small actions create significant systemic changes.	Urban wetland restoration maximizes ecological and social benefits.
Value-adding process reciprocity	Fostering regenerative relationships based on equitable contributions.	Circular economy models where all stakeholders benefit and strengthen one another.

Table 2.
Principles of regenerative design.

through management practices, efficient technologies, and environmental regulations aimed at reducing the damage caused by human activities. However, these efforts face significant limitations [27, 28].

Conventional sustainability focuses on maintaining existing resources to meet human needs, often treating the environment as a consumable service. While contemporary sustainability adopts a more holistic framework, this anthropocentric approach remains constrained, addressing symptoms like environmental degradation or resource inefficiency without tackling their root causes [27, 29].

In practice, sustainability has struggled to redirect socio-ecological trajectories toward a truly sustainable future [22, 30]. Environmental and social degradation persists at alarming rates, fueling a "planetary emergency." Although sustainability science has driven technological, policy, and economic advances, these often fail to deliver the transformative change needed to address these crises [27, 28, 31].

Ultimately, although sustainability has been a crucial stage in environmental thinking, its focus on minimizing harm and maintaining a neutral balance falls short. Moving forward requires regenerative frameworks that preserve, restore, and strengthen natural, social, and economic systems [32]. Unlike sustainability, which seeks medium-term balance (about one generation or 50 years), regenerative development emphasizes humanity's role within its environment, fostering co-evolution and long-term partnerships [25, 29].

3.3 Restoring and enhancing natural ecosystems through design

Cities like Finland, London, France, and Amsterdam have embraced holistic and regenerative design as the base for long-term strategies and public policies.

This approach positions design as a catalyst to achieve circular cities, fostering environmentally respectful economic and energy models, resource efficiency, resilient architecture, and food security. The need to foster a regenerative design culture has become urgent due to the accelerating pace of technological change, hyperconnectivity, automation, and the multidimensional impacts of the current health crisis. This culture looks for a systemic shift from an anthropocentric to an ecocentric perspective, emphasizing the complex relationship between humans and nature as the center of transformative change [33]. Regenerative design includes diverse strategies to establish a deep commitment to the place and cultural system where it is applied. It engages socio-ecological and cultural systems, addressing their inherent complexity to enhance their capacity for adaptation and evolution across multiple scales, benefiting natural ecosystems and human systems, as illustrated in **Figure 2** [27, 34, 35].

3.4 Key design principles for regenerative environments

3.4.1 Closed-loop systems and circular economy concepts

The traditional "linear mode" production model follows a "take, make, dispose" approach, relying on finite resources, generating significant waste, and driving environmental degradation [36, 37]. In the built environment, this model results in resource-intensive construction, excessive demolition waste, and high carbon emissions throughout a building's lifecycle, contributing to habitat destruction, climate change, and unsustainable urban areas.

In contrast, closed-loop systems and circular economy approaches aim to eliminate waste and maximize resource efficiency by continuously using materials [36]. These approaches prioritize sustainable construction practices, such as designing for disassembly, reusing materials, recycling construction and demolition waste, and using renewable energy sources for green infrastructure. The built environment can transform into a regenerative force by adopting circular principles that foster resilient urban spaces that minimize resource use, reduce emissions, restore natural systems, and enhance biodiversity.

As explained by Pugliese and Vertua [38], urban metabolism consists of the complex technical and biogeochemical flows within cities, which likens cities to living

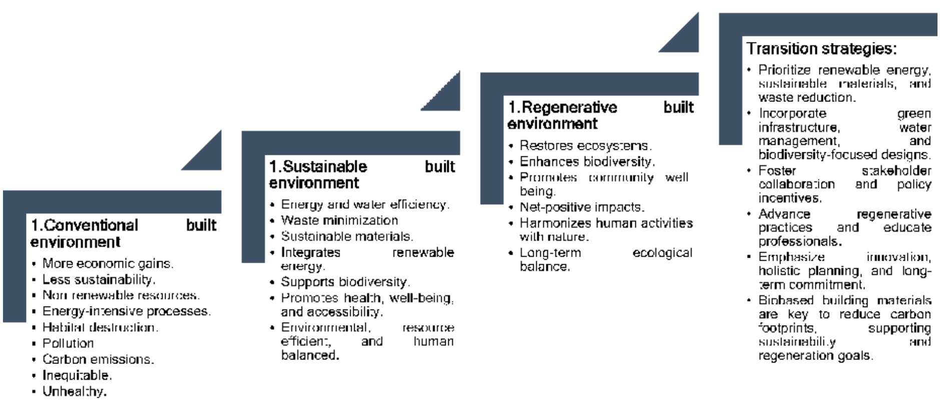

Figure 2.
Transition from conventional to sustainable and regenerative built environments, integrating natural ecosystems and human well-being.

organisms, emphasizing their complex flows of energy, water, and materials while generating waste and emissions. This perspective offers a new framework for addressing the environmental challenges of urban life.

Incorporating regenerative design into a circular economy framework involves creating systems that restore ecosystems, enhance resources, and support community well-being. Key strategies include adaptable, modular buildings designed for repair, disassembly, and reuse. Using locally sourced, renewable, and biodegradable materials reduces environmental impacts while fostering resilience. Green infrastructure, renewable energy, and water recycling further enable self-sufficient, low-impact designs. Collaboration and equitable practices transform the built environment into a restorative, net-positive contributor to society and nature.

Adopting circular economy principles requires changes in governance, organizational processes, and practices [37]. Circularity influences innovation strategies by prioritizing the selection of sustainable materials and energy sources and eco-effective design. It extends material and product lifecycles, promoting durability, modularity, and longevity while aiming to eliminate waste and pollution. This re-evaluation of economic activities aligns with the regeneration of nature and addresses humanity's social and ecological needs.

Implementing a circular economy in human-centered and regenerative built environment design involves rethinking waste management strategies to add value to waste through innovative approaches. In this context, bio-residues hold significant potential, strengthening circular bio-based economies [38]. For example, agricultural and food waste can be repurposed into new products [36], while incinerated and agricultural waste can be converted into alkali-activated materials and supplementary cementitious materials (SCMs) for sustainable construction [7]. Using lignocellulosic biomass for insulation avoids harmful emissions, enhances resource efficiency, and reduces greenhouse gases [6].

Incorporating bio-residues into construction materials supports a circular bio-based economy while mimicking natural cycles allows technical nutrients to be continually reused in industrial processes and biological nutrients to reintegrate safely into natural ecosystems [39]. Additionally, adopting nontoxic, healthy materials that align with nature ensures that buildings support sustainability and enhance human well-being, enabling the transition to net-positive, regenerative environments [40].

3.4.2 Systems thinking: Integrating ecological and human systems

Systems thinking provides a holistic framework for understanding complex systems by analyzing the interactions among their components [41]. It highlights the interconnectedness of economic, social, and ecological systems, enabling sustainable decision-making and problem-solving. Integrating human and ecological systems is essential for a regenerative built environment harmonizing nature, development, and well-being. Unlike traditional sustainability, regenerative design emphasizes restoring and enhancing ecosystems while addressing human needs.

The regenerative design incorporates ecological principles that mimic natural processes, such as the termite mound structure for air replacement and beaver-dug canals to restore streams [39]. Human systems' social, economic, and cultural aspects are equally important, as regenerative design fosters well-being through accessible green spaces, energy-efficient housing, and resilient infrastructure. Collaborative planning with local stakeholders ensures that projects respect cultural values and address specific needs.

Nature-based solutions (NbS) are key to integrating ecological and human systems. For instance, Burak et al. [42] highlight a cost-effective approach using chitosan to develop multilayered films with integrated color decoration, humidity sensing, and antiviral properties, offering industry applications. Other NbS for the built environment include plant-inspired innovations. Self-cleaning surfaces, mimicking the "Lotus Effect," create dirt- and water-resistant coatings ideal for windows and facades, reducing maintenance needs. Dynamic facades, inspired by the adaptive movements of plants like *Mimosa pudica*, respond to environmental changes, optimizing ventilation and natural lighting. Energy systems, modeled on photosynthesis, include solar panels and bio-batteries that replicate plants' energy-efficient processes, enhancing sustainability. Additionally, biomimetic sensors, designed based on plant mechanisms, can detect environmental pollutants or structural changes to improve safety and environmental monitoring. Together, these biomimetic approaches redefine building functionality and efficiency [43].

Plant-based materials offer vast potential as inspiration for innovations due to their resilience to stress conditions such as drought, flooding, and temperature extremes. They are a blueprint for resilience, inspiring water-efficient systems, drought-resistant materials, and eco-friendly construction products. Their lightweight, flexible, and durable structural properties align with circular economy principles, promoting waste reduction and resource efficiency [43].

Phytoremediation using plants like reeds removes toxins from wastewater, supporting ecological restoration, while integrating photovoltaic panels with microalgae enhances solar efficiency and sequesters carbon dioxide [5]. Soil generates thermal energy through geothermal heat exchange, microbial decomposition, solar absorption, and thermal mass storage, offering an efficient and renewable energy source. Vegetation, like green roofs, aids passive cooling and insulation, improving energy efficiency and reducing heat absorption. Microalgae-based bioreactors in HVAC systems filter pollutants, enhance indoor air quality, and increase oxygen levels. Green walls and indoor vegetation further improve IAQ while providing esthetic and psychological benefits, fostering healthier and more harmonious spaces. Additionally, green spaces promote mental well-being, reduce stress, and improve productivity in homes and offices [44].

Integrating ecological and human systems in building design includes bio-based materials, lifecycle assessments, and circular economy principles [39]. Circular housing, a key architectural trend, reduces environmental impact using recycled and renewable materials [15]. Inspired by living systems, such designs aim to eliminate waste and support business models focused on product collection, remanufacturing, and redistribution, reducing waste, emissions, energy demand, and costs.

By weaving ecological and human systems together, the built environment becomes a dynamic participant in ecological cycles, restoring degraded ecosystems and enhancing the quality of life. This holistic paradigm mitigates the environmental footprint of urbanization and creates thriving communities that coexist symbiotically with nature, paving the way for a regenerative future (**Figure 3**).

3.4.3 Designing for resilience and adaptability to climate change

Designing resilient buildings to climate change is critical to modern architecture and urban planning since they are tailored to withstand extreme weather events, adapt to changing environmental conditions, and reduce vulnerabilities for occupants. Adaptive and resilient design creates buildings that evolve with environmental

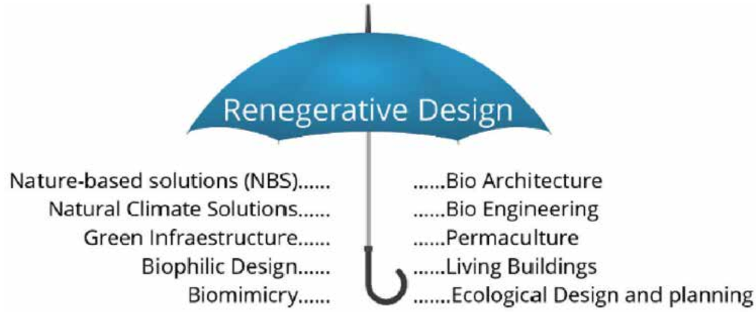

Figure 3.
Strategies under the regenerative design framework.

changes, inspired by nature's adaptability. Margariti et al. [45] redefine the design of physical interactions between humans and data within the built environment, addressing the pressing challenges of climate change. The authors identified three key areas for action, as presented in **Figure 4**.

Passive design strategies, such as shading devices, natural ventilation, and high-performance insulation, enhance energy efficiency and comfort by reducing reliance on energy-intensive systems. For example, textured facades inspired by elephant skin regulate temperature through shading and water retention, boosting energy efficiency [39].

3.4.3.1 Adaptability

Designing for climate resilience and adaptability incorporates innovations like Switchable Insulation Systems (SISs), which dynamically adjust thermal properties to suit environmental conditions [46]. Made from low-cost, eco-friendly materials, SISs are particularly effective in hot climates with high cooling demands. SISs enhance energy efficiency, lower greenhouse gas emissions, and cut operational costs while improving comfort, exemplifying how climate-responsive technologies can promote environmental and economic sustainability.

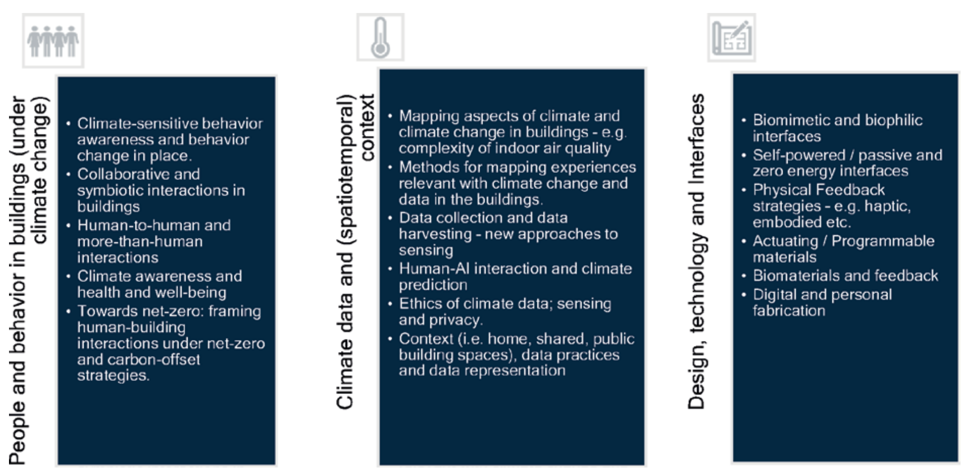

Figure 4.
Key topics on designing for resilience and adaptability to climate change. Author's own elaboration based on the work of Margariti et al. [45].

Structural resilience is equally important. Features like elevated foundations, water-resistant materials, and robust drainage systems in flood-prone areas mitigate risks for regions exposed to hurricanes or earthquakes, reinforced frames, aerodynamic designs, and flexible materials enhance resistance to extreme winds and seismic activity.

3.4.3.2 SBasic needs: water, energy, and well-being

Access to water and energy is a basic human need and fundamental for resilient designs. Rainwater harvesting, permeable surfaces, and greywater recycling reduce dependency on municipal systems and mitigate water scarcity risks. Green infrastructure, including vegetated roofs and walls, manages stormwater, lowers urban heat island effects, and fosters biodiversity. Renewable energy systems like solar panels, wind turbines, and energy storage ensure power continuity during disruptions and enhance self-sufficiency.

Despite initiatives like the 2015 Paris Climate Agreement, the eight hottest years on record occurred between 2015 and 2022, with 2016 being the warmest, and temperatures are projected to rise further as climate change intensifies [47]. Green building concepts seek to reduce or eliminate carbon emissions, addressing anthropogenic climate change, a critical factor in maintaining Earth's system stability [48]. This involves one or more strategies to integrate renewable energy sources or resource harvesting methods, depending on the geography, building, climate zone, etc.

A net-zero future demands balancing the shift to sustainable energy with maintaining resilience [47]. Many regions face challenges in energy efficiency and climate adaptation [49]. Older buildings often lack adequate insulation and passive solutions, leading to high energy consumption and poor climate resilience. Maintaining thermal comfort in tropical areas typically increases energy use and costs, affecting IAQ. Cool roofs provide an effective solution for hot climates. Biomaterial-based cool roofs with reflective coatings reduce indoor temperatures, improve energy efficiency, lower CO_2 emissions, and mitigate urban heat island effects, enhancing climate resilience and sustainability [50].

Designing for resilience and adaptability to climate change must also address air quality to safeguard public health. Climate change exacerbates air quality issues through extreme events like heatwaves and wildfires, increasing harmful pollutants such as tropospheric ozone. Effective strategies include green infrastructure to filter pollutants, adaptive HVAC systems for cleaner indoor air and renewable energy to cut emissions. Monitoring systems, waste management, and adherence to air quality standards are essential for creating adaptable, resilient environments that protect against climate-induced air quality challenges (**Figure 5**) [47].

3.4.3.3 Social and economic factors

Equally, climate-resilient designs address social and economic factors, prioritizing inclusivity and community well-being. Multi-use spaces that can serve as shelters during emergencies and adaptable layouts that accommodate evolving needs contribute to long-term functionality.

3.4.3.4 Tools and indicators

Designing for climate resilience and adaptability relies on advanced technologies and metrics. Tools like digital twins, predictive analytics, and Building Information

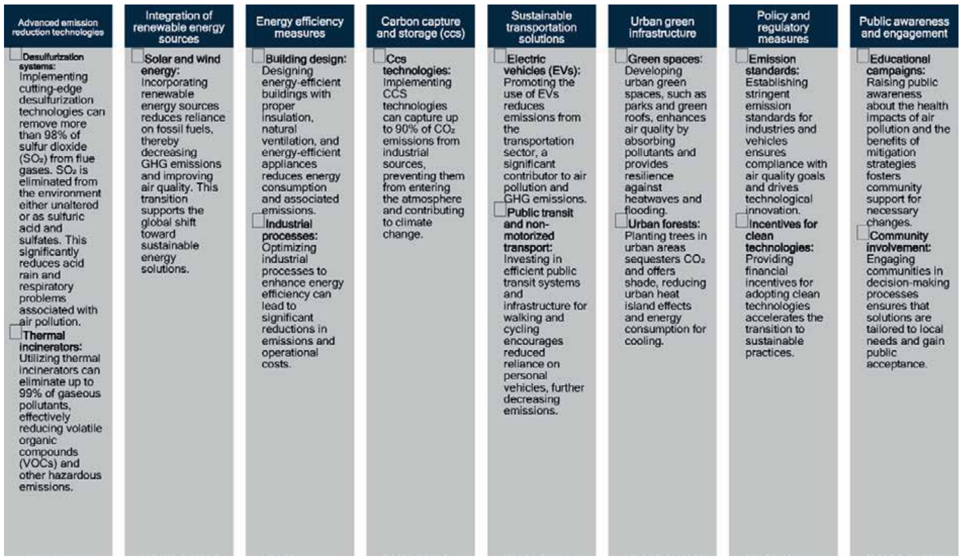

Figure 5.
Technological solutions for air pollution control to mitigate climate change. The author's elaboration was inspired by the work of Priyadarshani et al. [48].

Modeling (BIM) simulate climate impacts, optimizing building performance [15]. Quantifying the potential of biomaterials in numerical terms is crucial for mitigating climate change and reducing GHG emissions [51]. While lifecycle assessment (LCA) commonly assesses carbon and water footprints, complementary methods such as Material Flow Analysis (MFA), water footprint accounting, and lifecycle inventory (LCI) provide additional insights [51, 52].

Applying LCA and circular economy principles can help minimize carbon footprints and foster sustainability in construction. Key performance indicators for bio-based materials include tensile strength, insulation properties, lifecycle impacts, energy consumption, carbon footprint, and embodied energy [53]. Integrating these technologies and metrics transforms buildings into active contributors to resilience, environmental health, and economic stability, offering innovative and sustainable solutions to address climate challenges.

4. The role of biomaterials

Biomaterials may be considered a recent approach in the built environment; however, biomaterial science began around the mid-twentieth century within medical applications [54]. While biomaterial is mainly associated with the medical field, in the context of construction and the built environment, such materials are commonly referred to as "bio-based building materials" to distinguish them from bio-based materials used in other disciplines. Broadly, a building material qualifies as bio-based if it incorporates plant or animal biomass [55].

Bio-based building materials have been shown to enhance environmental sustainability and safety, offering lower cost, increased use of renewable resources, and recycling of municipal, agricultural, and food processing wastes, among other advantages [13, 15, 50, 56–58]. There is a wide range of bio-based and natural raw materials suitable for diverse applications in sustainable and regenerative practices [13, 38, 40, 57, 59]. These materials include wood, bamboo, straw, mycelium, agro-industrial residues, coconut husks, spent coffee grounds, natural fibers (e.g., hemp, bamboo, flax, kenaf), microalgae, eggshell powder, hydrangea stems, fungi (e.g., *Ganoderma lucidum*, *Pleurotus ostreatus*, *Fomitella fraxinea*, *Trametes versicolor*), humus, mussel shells, curaua, jute, sisal fibers, wool, lignocellulose, algae oil, waste edible oil residue, bio-based polyethylenes, thermomechanical pulp, corn, sugarcane, rice husk, barley straw, cellulose, and miscanthus.

Using bio-based building materials in the built environment offers transformative opportunities for construction and sustainability. These materials exhibit intrinsic properties, like biodegradability, lightweight structures, and flexibility, enabling customization and adaptability, making them ideal for prefabricated elements and unique architectural designs [6, 40, 53, 60]. Their potential is further amplified when integrated with innovative design and fabrication techniques such as bioinspired design approaches, including biomimicry and biomimetics [9, 22, 39, 61, 62], and additive manufacturing technologies [61, 63, 64].

From a sustainability perspective, these materials help reduce the carbon footprint as they are produced from renewable resources or repurposed waste, promoting a circular economy. Bio-based materials play a significant role in carbon sequestration due to the capacity of biomass to capture and store carbon throughout its lifecycle and at various stages of its lifespan [9, 58, 65]. During growth, plant-based biomaterials sequester carbon, significantly lowering the embodied carbon of buildings and contributing to climate change mitigation [38, 66]. Unlike conventional materials, biomaterials are cultivated rather than extracted, aligning with circular economy principles by serving as nutrients at their end of life rather than generating waste [40].

A widespread practice when using bio-based involves combining them with concrete. As one of the most widely used materials in the built environment, concrete benefits significantly from bio-based admixtures, which may provide potential enhancements in concrete formation processes, such as boosting strength, workability, and durability [56]. Incorporating biomass waste—such as wood shavings, bamboo [52], fibers [67, 68], rice, coconut and corn husks [69, 70], hemp, jute, sisal, flax, nettle, and pigeon pea [55, 65, 67, 71]—into construction materials has led to innovations like "vegetal concrete" [65], which promotes circularity by repurposing waste instead of disposing of it.

Moreover, coupling plant-based wastes with fast-growing species with shorter rotation periods, such as hemp and bamboo [58], further amplifies the potential for carbon sequestration. In many instances, bio-based building materials serve as the foundation for vernacular architecture, often designed harmoniously with local climatic conditions. These structures typically employ recyclable materials, generate minimal construction waste, and significantly reduce their ecological footprint [51].

Due to their natural insulating properties, these materials can also enhance thermal and acoustic performance. These features reduce energy consumption for heating and cooling, improve IAQ, and enhance occupant comfort [13, 65, 68, 70, 72]. Their lightweight nature and versatility make them easy to transport, handle, and adapt to innovative architectural designs [65]. For instance, mycelium-based structures mimic root-like networks, offering strength and lightweight properties for innovative applications [62, 73]. Additionally, these materials promote health, emitting low levels of volatile organic compounds (VOCs) [74]. They also have demonstrated durability and fire resistance under extreme conditions, particularly when combined with waste materials like rice husks and glass fines in substrates, as seen with bricks made from olive waste and mycelium composites [62, 73, 75].

Biomaterials foster a connection between humans and nature, enhancing comfort and well-being by offering esthetic and ecological connections between humans and nature. Their organic esthetic reflects sustainability, while their ecological and cultural significance can honor local traditions and promote regional identity. By conserving resources, reducing reliance on long-distance transportation, and offering malleable design options, biomaterials provide a sustainable, visually appealing alternative to conventional materials. Economically, their local production lowers transportation costs, supports regional economies, and ensures scalable supply using agricultural by-products while promoting cost-efficient construction and manufacturing processes [76]. These materials are especially valuable in regions abundant in biomass waste [14, 51, 76].

Despite their benefits, bio-based materials face challenges that require careful consideration [72]. Higher production costs and variability in performance often hinder adoption, while the lack of updated industry standards and clear specifications creates uncertainty in design and approval processes. Market acceptance can also be affected by odor, color, or combustibility, complicating market acceptance. Furthermore, their mechanical properties often differ significantly from traditional materials like concrete and steel, posing challenges in meeting strength and structural integrity requirements. Hybrid systems can provide solutions, but these, too, require tailored guidelines.

Durability remains a critical concern, as biomaterials are prone to degradation, moisture absorption, and biological attacks, which affect their long-term performance [53, 55, 69]. Effective treatments and design strategies, such as accommodating dimensional changes due to moisture, are essential to mitigate these risks. Specialized construction techniques may also be required, increasing costs and complexity. Key thematic gaps, including fire resistance, hygrothermal performance, and environmental impact assessments, further complicate their integration [72]. Health and safety considerations, such as volatile emissions and harmful residues, must also be addressed [57]. Overcoming these challenges requires robust standards, innovative designs, and a collaborative approach to unlock the full potential of biomaterials in sustainable construction.

In the context of climate change resilience, integrating advanced materials and technologies into the built environment is vital to enhance adaptability and energy efficiency. Alternative cementitious materials, supported by stricter environmental policies, provide sustainable options for reducing carbon emissions in the construction sector [77]. Innovations like phase change materials (PCMs) offer significant potential when incorporated into cementitious materials, improving thermal performance by storing and releasing heat as temperatures fluctuate, while combinations with nano silica enhance mechanical properties and durability, making buildings more robust against climate impacts [77]. Smart materials, such as those used in 4D printing for hygrothermal rehabilitation, address moisture and heat transfer issues, improving building envelope performance [49].

Adaptability to climate change extends beyond the built environment to humans themselves. For instance, adaptive fabric with emissivity regulation for the thermal comfort of humans is proposed by Li et al. [78], which adjusts its emissivity in response to the body's transition between dry and wet states, exemplifying innovative approaches to creating climate-adaptive built environments.

Finally, these materials align with regenerative design principles by minimizing environmental impact and restoring ecosystems through integration into renewable cycles. Together, bio-based building materials enable the creation of sustainable, resilient, and climate-adaptive built environments while enhancing the quality of life for their users (**Figure 6**).

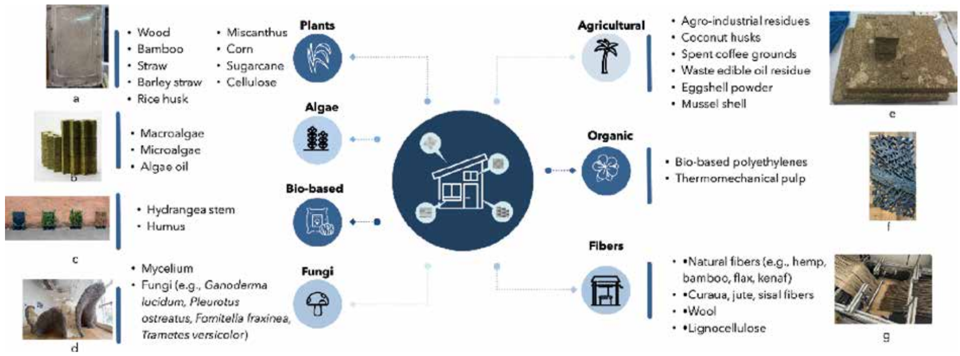

Figure 6.
Bio-based and natural raw materials classification: plants [79], algae [66], bio-based [80], fungi [81], agricultural [70], organic [82], fibers [83]. The author's elaboration is based on the works of Sutkowska et al. [13, 38, 40, 57, 59]. All images were reproduced under the CC BY-NC 4.0.

5. Discussion: Highlighting cases of regenerative design using biomaterials

One of the central questions addressed here is how biomaterial-based strategies and emerging technologies can enhance indoor air quality, thermal comfort, and environmental regeneration in the built environment, particularly when applied across diverse case studies. Analyzing projects such as Civano (Arizona), Playa Viva (Mexico), and examples from Denmark, Finland, and Turkey explores innovative approaches addressing critical environmental and societal challenges. The findings highlight that integrating biomaterials and advanced technologies reduces carbon footprints, promotes regenerative practices, and improves ecosystem health and life quality. A review of diverse studies reveals two primary approaches: those focused on individual building elements and those addressing the broader built environment, highlighting biomaterials' key role in shaping regenerative design.

5.1 The net-zero green building

Achieving net-zero carbon buildings impacts occupant health and urban sustainability, and this needs to be addressed during the entire building's life cycle. Existing literature reports various approaches across life cycle phases [15, 84, 85].

In the design phase, Building Information Modeling (BIM) has been shown to reduce environmental impact [84]. BIM via Revit combined with biomaterials, considering material recycling, was employed in a case study in Jalisco and Querétaro (Mexico), evaluated via simulation in the Green Building Studio software. One case used biomaterials such as wood, raw soil, bamboo, and straw bales; the other used traditional materials. Results demonstrated significant CO_2 emission reductions when using biomaterials instead of concrete [15]. However, limitations included insufficient flexibility for custom material inputs and related data support.

At the construction phase, biomaterials can significantly reduce the building's embodied carbon. An Australian office case study reported that net-zero embodied carbon was achievable when considering biogenic emissions stored in timber, glass wool, and straw, although only temporarily, for up to 19 years, where about 45% of upfront embodied carbon reduction was achieved [85]. The authors introduced a new term, "temporal net-zero embodied carbon," to describe when a building ceases to act as a temporary carbon sink [85]. Again, limitations arose regarding supporting related data, especially in the data reliability and availability, highlighting hybrid data rather than processed data.

5.2 The bio-symbiotic built environment

A holistic approach is needed to achieve climate-responsive, regenerative, and human-centered built environments successfully. The "Urban Bio-Symbiosis" concept exemplifies such an approach by integrating green infrastructure, urban farming, and bio-waste valorization [86]. A noteworthy case is the Playa Viva eco-resort on Mexico's Pacific Coast [87], which focused on creating a "culture of co-evolution" between the built environment, community, and natural ecosystems. Initially committed to sustainability, the project shifted to a regenerative development approach, emphasizing long-term socio-ecological harmony.

Effective waste management is vital for supporting bio-symbiotic systems. Nearly 90% of agricultural waste is in landfills, highlighting the need for better waste management practices [88], which may be of great value in a bioeconomy circular approach [89]. For instance, it can be repurposed into bio-based plastics [84] or other functional biomaterials to support green infrastructure [90].

Community gardens can serve as an example of contributing to health, food security, and urban resilience [68]. They can demonstrate sustainable urban practices, showing how locally sourced, biodegradable materials can support food production and community well-being while reducing environmental footprints. Urban farming areas can also support biomaterial production by cultivating plants to manufacture biodegradable materials for green infrastructure. These gardens enhance local food production, reducing reliance on external supplies vulnerable to climate disruptions while fostering open spaces for recreation and education [91].

Additionally, community gardens close the loop in a circular economy by composting organic waste into bio-based fertilizers, biochar, and cellulose-based biomaterials. These materials can be used for creating bio-bricks, garden beds, and biodegradable tools like stakes or trellises, demonstrating sustainable urban practices that integrate biomaterials to reduce environmental footprints while enhancing community well-being.

Civano in Tucson, Arizona [92], is a model of sustainable urban planning tailored to its local context. Initiated in the 1980s with governmental support, it integrated solar technologies, water conservation, and local materials alongside strategies like cooling towers and rainwater harvesting. Despite challenges, such as limited expertise in sustainable practices, Civano achieved a 50% reduction in energy consumption and a 65% decrease in potable water use. Additionally, it promoted vehicle reduction, job creation, and affordable housing, and it preserved 35% of open space, enhancing sustainability and quality of life. Homes built with straw bales and adobe reduced heating and cooling loads by 30%. The data highlights the synergistic role of biomaterials and conservation strategies in achieving thermal comfort and reducing environmental impact.

Civano exemplifies how community-oriented projects can contribute to sustainability by minimizing energy reliance and promoting ecosystem regeneration. Civano's strategies directly address the research question by improving thermal comfort and air quality through passive cooling techniques while enhancing environmental regeneration via native biodiversity. Civano's approach integrates biomaterials more extensively into residential infrastructure than other projects like Playa Viva.

Playa Viva, an eco-resort on Mexico's Pacific coast [87], adopts regenerative design principles, harmonizing the built environment with natural ecosystems and community needs. It integrates biomaterials and permaculture, achieving an 80% reforestation rate across 200 acres, reducing cooling demands by 40%, and increasing native species populations. These measures demonstrate regenerative design capacities for restoring ecosystems, thermal comfort, and IAQ enhancement.

On the other hand, in more specific studies, Danish research highlights fast-growing materials like straw and grass, reducing land use and carbon footprints [93], while Finnish studies show timber frames cut land use by 61% and achieve a 290% cost reduction compared to concrete [94]. The analysis reveals that bio-based materials reduce land use by up to 61% and lower construction costs significantly. Finnish timber frames, when compared to concrete, achieve a 290% cost reduction in achieving positive climate effects. These results validate the potential of biomaterials to scale sustainable construction while addressing economic barriers, particularly in policy-driven contexts. When juxtaposed with Civano and Playa Viva, these cases emphasize the role of policy and innovation in advancing biomaterial adoption for climate-responsive solutions.

Moreover, a case study in Turkey [95] demonstrates the use of traditional materials integrated with modern technologies to improve thermal efficiency, while microalgae research [5] introduces new energy production and air quality improvement methods. Prototypes in Turkey reduced U-values by up to 40%, while microalgae systems showed enhanced biomass production and CO_2 absorption in urban settings. These innovations demonstrate the synergy between traditional knowledge and advanced technologies in addressing climate challenges.

The case studies analyzed demonstrate that strategies based on biomaterials and emerging technologies are essential for improving indoor air quality, optimizing thermal comfort, and regenerating the built environment. Other studies that support this view were evaluated [15, 42, 50, 66, 85, 96], highlighting that these elements are key to regeneratively addressing the built environment's challenges. These studies complement the presented cases, showing how these solutions can be adapted to different cultural and climatic contexts, contributing to a broader sustainable development.

6. Conclusions

More climate-responsive built environments are needed to provide sustainable and resilient housing, especially for climate-risk-vulnerable people. Implementing biomaterials together with a human-centered and regenerative design can contribute to a climate-responsive built environment by addressing people's health, reducing embodied carbon footprint, and providing greener infrastructure. Integrating biomaterials in the built environment redefines sustainability paradigms and opens new possibilities for regenerating the relationship between human and natural systems.

Many documents focus on one aspect of the built environment, e.g., buildings' envelope and indoor comfort (building scale), instead of contemplating the entire built environment, such as the ecosystem-community dimension. However, the individual focus of each study can be merged as per the goal they contribute toward a more climate-responsive built environment in all its dimensions. Therefore, by highlighting the role of biomaterials, two broader cases can be conceptualized: "the net-zero green building" by looking at the studies related to one element of the built environment and "the bio-symbiotic built environment" studies that propose an approach to consider most of the built environment dimensions.

The case studies presented, from the community-based approach of Civano in Arizona to the ecological symbiosis of Playa Viva in Mexico, highlight that biomaterials are technical solutions and tools that enhance collective well-being and connection to the environment. These experiences reinforce how adopting local materials and regenerative strategies reduces carbon emissions, strengthens local economies, and promotes biodiversity.

Finally, this chapter provides evidence that biomaterials are fundamental to meeting the challenges of regenerative design in the twenty-first century. Beyond the environmental benefits, these strategies foster a cultural shift toward a more holistic and systemic view of design, where buildings serve people and the ecosystems that sustain them. It is imperative to move toward a design approach prioritizing the co-evolution of natural and anthropogenic systems, ensuring a more sustainable and harmonious future for future generations.

Acknowledgements

The authors would like to thank, for their collaboration, the Research Groups Design, Manufacturing and Materials (DM+M), Energy and Comfort in Bioclimatic Buildings (ECEB, https://eceb.utp.ac.pa/) both as part of the Faculty of Mechanical Engineering (https://fim.utp.ac.pa/), and the Research Group Sustainable Construction UTP as part of the Experimental Research Center within the Technological University of Panama (https://utp.ac.pa/). Likewise, special thanks to the Sistema Nacional de Investigación (SNI) for its support.

DOI: http://dx.doi.org/10.5772/intechopen.1009900

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Chapter 4

Incorporating Vegetation into Building Design

Rolien Terblanche

Abstract

Biophilia and biophilic design emphasize the innate human connection with nature, advocating for the integration of natural elements into the built environment. By incorporating green infrastructure such as green roofs, living walls, and urban vegetation, architects and urban planners can enhance sustainability, biodiversity, and human well-being. These installations provide ecological and psychological benefits, including improved air quality, microclimate regulation, and enhanced mental health. However, successful implementation requires careful planning, appropriate maintenance, and climate-responsive design. Despite their potential, green infrastructure projects often face challenges related to structural integrity, drainage, maintenance, and climate adaptability. Notable failures, such as the collapsed green roof in St. Charles, Illinois, and the deteriorated living wall at Paradise Park Children's Centre in London, highlight the consequences of poor planning and insufficient upkeep. Key lessons from these cases underscore the necessity of structural assessments, proper drainage systems, and specialized maintenance to ensure longevity and functionality. Assigning inexperienced maintenance teams, as seen in the Westfield Warringah Mall project, can lead to rapid degradation and financial losses. To maximize the benefits of biophilic design, future projects must integrate rigorous structural planning, climate-appropriate plant selection, and long-term maintenance strategies. By addressing these challenges through innovative solutions, policy support, and region-specific research, cities can successfully incorporate green infrastructure into urban landscapes. Learning from past failures will enable the development of resilient, sustainable, and esthetically enriching environments that contribute to both ecological and human well-being.

Keywords: green roofs, green facades, greenery, vegetated buildings, biophilic design, living walls, planted walls, green rooftop systems, green cities

1. Introduction

The concept of biophilia describes the innate human tendency to connect with nature and natural elements, emphasizing its role in well-being and environmental harmony [1]. Biophilic design encompasses direct connections with nature, biomimetic patterns, and spatial arrangements inspired by natural landscapes [2]. By incorporating vegetation into urban spaces through green roofs, vertical gardens, and indoor sky gardens, this design philosophy fosters ecological balance [3] while addressing contemporary challenges such as climate change and urban stress [4].

The integration of vegetation into building design offers a range of benefits, spanning environmental [5], physical [49], psychological [6], and economic aspects [7]. As urbanization accelerates, incorporating green infrastructure has become essential for mitigating climate challenges and enhancing urban sustainability.

While integrating vegetation into building design offers numerous benefits, it also presents significant challenges. High initial costs, structural reinforcements, and specialized maintenance increase financial and logistical demands [8]. Water management issues [9], plant selection limitations [10], and the risk of pests, diseases [11, 12], and fire hazards further complicate implementation [13]. Additionally, the lack of local research and skilled professionals, particularly in developing regions, hinders widespread adoption [12, 14]. Ensuring climate viability and sustainable irrigation remains a key concern, especially in extreme weather conditions [15]. Despite these challenges, strategic planning and technological advancements can help overcome these barriers, making green infrastructure a viable long-term solution.

In support of biophilic design, this chapter aims to (i) elaborate on the various methods of incorporating vegetation into building design, (ii) discuss the expected advantages and disadvantages, as well as (iii) present examples of successes and failures. Lastly, this chapter concludes with lessons learnt and direction forward.

2. Biophilia and biophilic design

The concept of biophilia has been defined in various ways within the literature. It has been characterized as the "deep-seated need of humans to connect with nature" [16] and as an "innate affection towards nature and natural elements" [1]. Another definition conceptualizes biophilia as a biologically driven inclination to connect with the natural environment [17].

Although these definitions differ in wording, they share two fundamental aspects. First, they propose that biophilia is an inherent characteristic of humans, suggesting that it is not a learned behavior but an intrinsic trait. Second, they all emphasize the human desire to connect with or associate with nature. Thus, despite slight variations in expression, these definitions are conceptually aligned, demonstrating a broad consensus within the literature regarding the meaning of biophilia.

The term biophilia was first introduced by Erich Fromm in 1964 [18]. However, it was later popularized [19] and formally hypothesized by Edward O. Wilson, a Harvard University scientist and award-winning author. In his book Biophilia (1984), Wilson posited that humans possess an innate and evolutionarily driven affinity for the natural world [20].

Biophilic design involves the integration of nature, natural elements, or biomimetic designs into the built environment, which refers to human-made buildings and infrastructure [21]. Gillis and Gatersleben [22] define biophilic design as "a design philosophy that encourages the use of natural systems and processes in the design of the built environment." This approach aims to create spaces that foster a connection between humans and nature, enhancing well-being and sustainability.

Browning, as cited in [2], identified three categories of biophilic design attributes. The first category, "nature in the space," involves the direct incorporation of natural elements such as plants and unobstructed views of nature within a built environment.

The second category, "natural analogues," refers to the use of patterns, materials, and shapes that mimic natural forms, thereby evoking an indirect experience of nature. The third category, "nature of the space," pertains to the spatial arrangement of design elements and furniture in a way that emulates natural landscapes. This approach aligns with the theory of prospect and refuge, which suggests that certain spatial configurations can evoke a sense of security and comfort.

This chapter draws from the first category, which involves the incorporation of plants into building design.

3. Methods to incorporate vegetation into buildings

There are various ways to incorporate vegetation into buildings. These methods can be categorized according to horizontal spaces, vertical spaces, and green pockets (three-dimensional green spaces) [23].

3.1 Horizontal green spaces

Horizontal spaces consist of green rooftop gardens and can be classified into extensive, semi-extensive, and intensive systems, each differing in soil depth, vegetation type, maintenance requirements, structural load, and accessibility. These distinctions determine their suitability for various buildings and environmental objectives [24]. A green roof (GR) is an extension of either an existing or newly constructed roof that integrates a multi-layered system, consisting of a waterproofing membrane, a root barrier, a filtration layer, a drainage system, and a lightweight growing medium, along with vegetation [25].

3.1.1 Extensive green roof

An extensive green roof is a lightweight, low-maintenance system designed primarily for environmental benefits rather than human use. It can be installed on a concrete or timber roof. It typically has a shallow soil depth ranging from 5 to 15 cm and supports drought-tolerant plants such as sedums, mosses, and hardy grasses. With a low weight load of around 60–240 kg/m^2, extensive green roofs can be installed on many buildings without significant structural reinforcement [26]. Maintenance is minimal, relying mainly on natural rainfall, making it an excellent choice for buildings where upkeep needs to be minimal. While these green roofs contribute to insulation, stormwater management, and reducing the urban heat island effect, they offer limited biodiversity and are generally not designed for public access. They are most commonly used on commercial and industrial buildings with restricted structural capacity or where sustainability is a priority [27]. This concept can be seen in **Figure 1**.

3.1.2 Semi-extensive green roof

A semi-extensive green roof is a hybrid between extensive and intensive systems, providing a wider variety of plant life while keeping maintenance requirements relatively low. It features a moderate soil depth of 15 to 30 cm, which allows for the growth of low-lying plants, small shrubs, herbs, and some perennials. This system is built on a concrete roof. With a weight load of 240–500 kg/m^2, it requires a stronger structural foundation than an extensive green roof but remains lighter than an

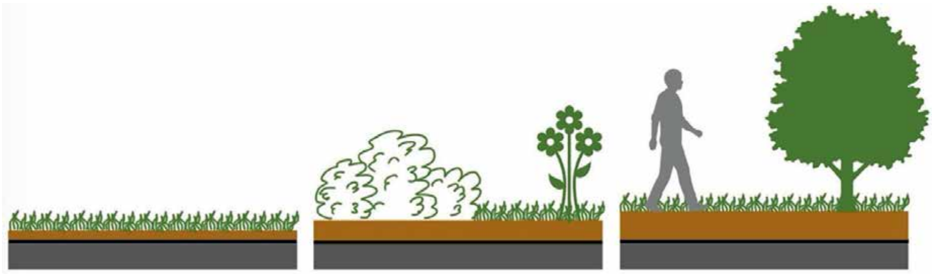

Figure 1.
Types of horizontal green spaces. Extensive green roof (left), semi-extensive green roof (middle), intensive green roof (right) (author).

intensive one. While it needs occasional irrigation and moderate upkeep, it supports greater biodiversity by attracting pollinators and small wildlife. Semi-extensive green roofs can sometimes be designed for limited human use, offering both esthetic and ecological benefits without the high costs associated with fully intensive systems. They are well-suited for commercial and residential buildings looking to balance sustainability, esthetics, and manageable maintenance [28]. Examples of buildings with semi-extensive green rooftop systems include: ACROS Fukuoka Prefectural International Hall [29]. **Figure 1** illustrates this concept.

3.1.3 Intensive green roof

An intensive green roof, also known as a rooftop garden, is a fully developed landscaped space featuring deep soil layers of 30 cm to 200 cm on a concrete roof with a maximum pitch of 5 degrees [30]. This depth allows for the growth of a diverse range of vegetation, including lawns, flowers, shrubs, and even trees. Due to its high weight load—often exceeding 500 kg/m^2—it requires significant structural reinforcement. Intensive green roofs demand regular irrigation, fertilization, pruning, and other maintenance efforts. However, they provide the highest level of biodiversity, supporting a variety of plant and animal life while also improving air quality. Unlike the other two types, intensive green roofs are specifically designed for human use, often incorporating pathways, seating areas, and recreational spaces. While they offer the most esthetic and social benefits, they are also the most expensive to install and maintain. They are best suited for residential complexes, office buildings, hotels, and other urban spaces where green areas can be integrated into daily activities [28]. Examples of buildings with intensive green rooftop systems include: Khoo Teck Puat Hospital; ParkRoyal on Pickering; Kampung Admiralty [29]. **Figure 1** illustrates the three different types of green rooftop systems.

3.1.4 Revised terminology based on function and vegetation

Kotze et al. [31] pointed out a flaw in the abovementioned terminology and categorization. Substrate thickness is often regarded as a primary factor in distinguishing between extensive and intensive green roofs; however, there is little consensus on the precise boundary between these categories. Berndtsson [32], for example, identified an overlap in classifications based on substrate depth and cautioned against relying solely on this dichotomy when interpreting roof functionality. The ambiguity of this classification system is further compounded by the fact that substrate characteristics, such as organic matter content, water-holding capacity, and nutrient availability, do not exhibit a clear distinction between extensive and intensive roofs [31].

Another example of an imprecise and, therefore, weakly informative classification is the general assertion that extensive green roofs are lighter than intensive ones [33]. In reality, the weight of a vegetated roof is determined by the materials used in the substrate and other structural layers. Consequently, a roof with a thinner substrate may not necessarily be lighter, nor a roof with a thicker substrate necessarily heavier. Since weight and substrate depth do not consistently correlate, they cannot be used as definitive criteria for categorizing roof types. Ultimately, they argue that the extensive/intensive classification is a misleading conceptual construct based on generalized assumptions rather than precise definitions and empirical data [31]. Based on the two most important components (function and vegetation), Kotze et al. [31] propose classifying and naming vegetated roofs according to their primary function and vegetation type. This approach could lead to designations such as "Stormwater Meadow Roof," "Biodiversity Meadow Roof," "Scenic Moss Roof," "Restorative Forest Roof," "Restorative Meadow Roof," "Biodiversity Chaparral Roof," "Pollinator Flower Roof," "Habitat Connectivity Grassland Roof," or "Multifunctional Meadow Roof."

3.2 Vertical green spaces

Vertical green spaces can be categorized into a direct green facade, an indirect green façade, perimeter flowerpots and living walls.

3.2.1 Direct green facade

A direct green facade is a system in which climbing plants, such as ivy with small adhesive roots, attach themselves to designated anchor points on the surface of a wall and grow directly along it. This is also known as a traditional green façade [34]. The University of Cape Town boasts with several campus buildings that have a direct green façade. **Figure 2** illustrates the direct green façade in image A.

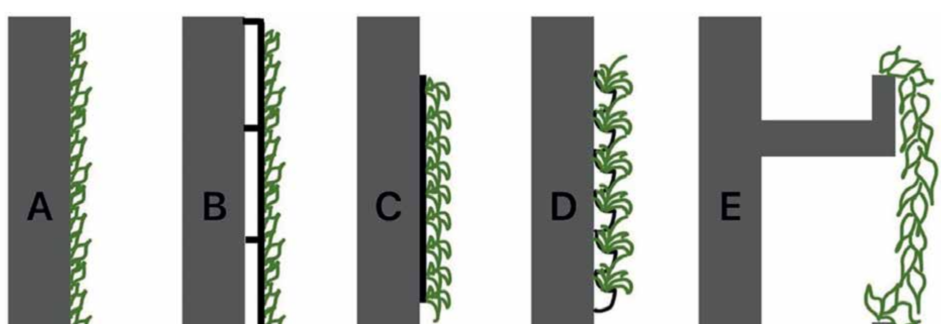

Figure 2.
Types of vertical green spaces. A: Direct green façade; B: Indirect green façade; C: Continuous living wall; D: Modular living wall; E: Perimeter flowerpots (author).

3.2.2 Indirect green facade

In contrast, an indirect green facade (double skin green façade) incorporates structural supports, such as modular trellises or continuous guiding systems, to facilitate plant growth. This system typically includes an air gap between the support structure and the wall, allowing for improved ventilation and reducing potential damage to the building's surface [35]. Like vegetated roofs, green vertical systems can be classified as either extensive or intensive. Extensive systems are relatively simple to construct and require minimal ongoing maintenance. The direct green façade and indirect green facade are extensive systems and are rooted in the ground. Examples of buildings with indirect green facades are: One Central Park in Sydney [36]; Consorcio Building; Council House 2 (CH2); M6B2 Tower of Biodiversity; Le Nouvel KLCC [29]. **Figure 2** illustrates the indirect green façade in image B.

3.2.3 Perimeter flowerpots

Perimeter flowerpots, when integrated into the architectural composition of a facade, are used to cultivate hanging potted shrubs around the building, forming a continuous green curtain [34]. Intensive systems involve more complex implementation and necessitate a high level of continuous upkeep. Perimeter flowerpots fall under the intensive system category [34]. The development, 1000 Trees, in Shanghai could be considered an example. **Figure 2** demonstrates this concept with image E.

3.2.4 Living walls

Living walls can be classified into two primary types: continuous green walls, which utilize a continuous screen or geotextile felt, and modular green walls, which consist of trays or containers designed to support plant growth [37]. These concepts are illustrated in **Figure 2**, images C and D. Living walls can either be external or internal, each having distinct advantages or disadvantages. Examples of buildings with livings walls on their facades include: CDL's Tree House; Santalaia; East Village; Check Point; School of the Arts Singapore (SOTA) [29].

3.3 Green pockets: Three-dimensional green spaces

Green pockets are three-dimensional (3D) green spaces integrated into buildings, exhibiting a wide range of spatial forms and layouts. The term "green pocket" is used for three primary reasons [38].

First, green pockets exist within 3D volumes, emphasizing their capacity to support intensive vegetation. Their height and width are designed in conjunction with the necessary depth for plant growth. To accommodate larger plants, including trees with full canopies, the substrate depth must exceed 25 cm, which is the maximum depth of a semi-extensive green roof capable of supporting only small plants [31]. These "pockets" contain various biotic elements (such as plants, animals, and microorganisms) as well as abiotic components (including soil substrates and water), fostering a diverse ecological environment [38].

Second, green pockets offer flexibility in spatial configuration and can be integrated at various locations within a building. Unlike conventional horizontal and vertical green designs, which are often confined to specific surfaces, green pockets can be incorporated three-dimensionally across building exteriors, interiors, and different structural levels. They function as transitional spaces that blur the boundary between natural (green) and artificial (gray) environments, rather than merely acting as partitions between indoor and outdoor spaces [38].

Third, green pockets serve as accessible green spaces in urban environments, promoting coexistence between humans and other living organisms. By incorporating trees, shrubs, and other plant species within cities, green pockets enable urban dwellers to experience greenery beyond suburban homes with private gardens. These spaces not only provide habitats for plants and other species within human-built environments but also function as micro-ecosystems that connect with larger ecological networks, contributing to urban biodiversity and environmental sustainability [38]. Green pockets can be incorporated as green balconies, indoor sky gardens, and green atriums. These concepts are illustrated in **Figure 3**.

3.3.1 Green balcony

A green balcony with integrated features is a carefully designed outdoor space that incorporates various structural and functional elements to enhance greenery, sustainability, and usability. Unlike conventional balconies with simple potted plants, this type of design integrates green infrastructure into the built environment, offering both esthetic and ecological advantages [23].

One of the fundamental components of an integrated green balcony is the use of built-in planters and vertical greenery. Planters integrated along railings or walls provide a stable environment for plant growth, while vertical gardens, such as trellises, modular green walls, or hydroponic systems, maximize green space efficiency. Additionally, climbing plants supported by wires or lattice structures create a natural green curtain that offers shading and privacy [39].

To ensure efficient water management, smart irrigation systems play a crucial role in green balcony design. Drip irrigation or automated watering systems help optimize water distribution and reduce maintenance efforts. Additionally, water retention systems, such as self-watering planters or rainwater collection mechanisms, contribute to sustainability by conserving water resources [15].

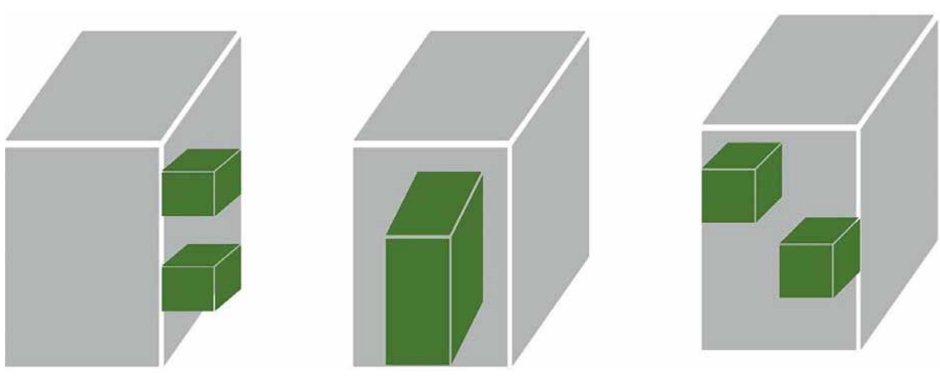

Figure 3.
Types of green pockets/3D green spaces. Green balconies (left), atrium garden (middle), indoor sky gardens (right) (author).

A well-integrated green balcony can also serve as a multifunctional space. Seating areas combined with built-in planters provide a relaxing environment, while edible gardens featuring herbs, vegetables, or fruit-bearing plants offer opportunities for small-scale urban farming. Furthermore, elements such as pollinator-friendly plants and small birdhouses support urban biodiversity by attracting beneficial wildlife [38].

In addition to esthetics and sustainability, structural and safety considerations are essential when designing an integrated green balcony. Lightweight growing media and securely anchored planters prevent excessive structural loading, ensuring safety in high-rise buildings. Proper drainage systems are crucial to preventing water accumulation and potential damage to the building. Moreover, selecting wind-resistant plant species and installing protective barriers help maintain the stability of the greenery in exposed urban settings. By integrating thoughtful design elements, a green balcony transforms an ordinary outdoor space into a sustainable, comfortable, and ecologically beneficial extension of urban living [23].

Examples of buildings with magnificent green balconies include Bosco Verticale in Milan [40]; Agora Garden Tower in Taipei, Taiwan [41]; The Met; Clearpoint Residencies; Huaku Sky Garden; Trudo Vertical Forest; Ravel Plaza [29].

3.3.2 Indoor sky garden

An indoor sky garden is a high-rise, enclosed green space designed within a building, typically on upper floors or rooftops, that integrates natural elements such as plants, trees, and water features in a controlled indoor environment. Unlike traditional rooftop gardens, indoor sky gardens are protected from external weather conditions by glass facades or other enclosures, allowing for year-round greenery regardless of climate. They often feature large windows, skylights, or transparent walls to maximize natural light while providing panoramic city views. The vegetation in these gardens can include a mix of small plants, shrubs, and even trees, supported by advanced irrigation and ventilation systems to ensure optimal growth.

Some well-known examples of indoor sky gardens include the Sky Garden in London [42], the Futuristic Gardens at Marina One in Singapore [43], and the Cloud Forest at Gardens by the Bay in Singapore [44]. These spaces showcase how integrating greenery into tall structures enhances urban sustainability, biodiversity, and human well-being while redefining how nature and architecture coexist in modern cities.

3.3.3 Atrium garden

An atrium garden is a type of indoor garden located within the atrium space of a building, often situated in the central, open area of a structure. This garden is typically surrounded by the building's walls, with an open or glazed roof that allows natural light to penetrate, creating a bright and airy environment [23]. Hotel Jakarta is a perfect example of a successfully implemented atrium garden [45].

4. Advantages

Advantages of vegetation incorporated into building design can be divided into three categories: Environmental, physical, and phycological and economic benefits.

DOI: http://dx.doi.org/10.5772/intechopen.1010089

4.1 Environmental advantages

4.1.1 Microclimate

The rapid expansion of urban areas has led to significant vegetation loss, contributing to the urban heat island (UHI) effect, where urban regions exhibit higher temperatures than their surrounding rural areas [46]. The incorporation of vegetation into urban planning plays a crucial role in mitigating this effect. The increased integration of green infrastructure within urban environments helps lower both air and surface temperatures. Vegetation within urban design influences the thermal environment by providing shade, reflecting solar radiation through canopy cover, and reducing surface temperatures, which subsequently facilitates heat dissipation through convection [47].

Furthermore, evapotranspiration, the process by which vegetation releases moisture into the atmosphere, contributes to cooling by converting latent heat from incident solar radiation, thereby reducing the emission of longwave radiation from the ground [48].

4.1.2 Pollutant deposition and absorption: Enhanced air quality

With increasing urbanization, individuals residing near high-traffic areas are more exposed to vehicular emissions and air pollution. Additionally, urban layouts significantly influence air quality and contribute to global climate change. Vegetation plays a crucial role in improving air quality by absorbing pollutants such as sulfur dioxide (SO_2), carbon dioxide (CO_2), and particulate matter (PM). This process helps to reduce respiratory illnesses and enhance overall environmental conditions within urban areas [4]. A study indicates that approximately 0.09 square meters of vegetated wall area has the capacity to filter the air for approximately 9.3 square meters of office space. From a broader perspective, the greening of a single wall on a building located within a street comprising 50 buildings is functionally equivalent to the planting of 50 trees along that street [49]. Furthermore, research demonstrated that an indoor sky garden can remove more than 80% of indoor contaminants such as VOCs and CO_2 [50].

4.1.3 Urban stormwater management

The use of permeable, vegetated surfaces in place of hard, impermeable surfaces enhances drainage efficiency and reduces surface runoff and mitigates the risk of flooding in an urban setting [51].

4.1.4 Urban reconciliation ecology

Urban reconciliation ecology is an approach that seeks to integrate biodiversity and ecological functions into human-dominated landscapes, particularly within cities. This concept focuses on modifying built environments to support native species, restore ecological processes, and enhance environmental sustainability while maintaining urban functionality [3]. In this context, living roofs (green roofs) and living walls (green facades and vertical gardens) play a critical role in fostering urban biodiversity, improving ecosystem services, and mitigating the adverse effects of urbanization [5].

4.1.5 Enhancing biodiversity and habitat connectivity

One of the key objectives of urban reconciliation ecology is to create habitats for flora and fauna within urban areas, enabling species to coexist with human infrastructure [3]. Living roofs and walls provide essential microhabitats for birds, pollinators, and insects, contributing to urban biodiversity. By incorporating native plant species and structurally diverse vegetation, these green infrastructures help sustain pollinators (e.g., bees and butterflies), small mammals, and avian species, thereby supporting habitat connectivity across fragmented urban landscapes [5].

4.2 Physical advantages

4.2.1 Physical health

Residents of green buildings are likely to experience a reduced incidence of symptoms associated with Sick Building Syndrome (SBS), including dizziness, headaches, nausea, coughing, fatigue, nosebleeds, respiratory issues, blurred vision, wheezing, sneezing, ear infections, and skin rashes. Furthermore, it is highly probable that chronic health conditions such as asthma (in both adults and children), chronic obstructive pulmonary disease (COPD), allergies, and cardiovascular disorders will exhibit symptom alleviation in such environments [52, 53].

4.2.2 Noise reduction

Green facades and vegetated walls act as natural barriers to sound transmission, reducing the penetration of external noise into buildings. The foliage, plant layers, and growing medium function as porous materials that scatter, diffract, and absorb incoming sound waves. This process helps to lower sound pressure levels (SPL), particularly in areas exposed to traffic noise and urban disturbances [54].

Vegetated surfaces improve sound absorption by minimizing sound reflection from hard building materials such as concrete, glass, and metal. The leaves, stems, and soil act as acoustic absorbers, dissipating sound energy rather than reflecting it. The porosity and texture of vegetation enhance the absorption coefficient, making green facades effective at mitigating indoor and outdoor noise pollution [54].

Reverberation time (RT60), which refers to the time taken for sound to decay by 60 dB in a given space, is a crucial parameter in architectural acoustics [55]. High reverberation times result in excessive echo and poor speech intelligibility, particularly in large atriums, courtyards, and open-plan buildings. Vegetated surfaces help to optimize reverberation time by absorbing sound waves rather than allowing them to bounce off hard surfaces. This creates a balanced acoustic environment, improving both speech clarity and overall auditory comfort in indoor and semi-outdoor spaces [56].

Therefore, indoor living walls can enhance the acoustic comfort of interior spaces by increasing both sound insulation and the surface area for sound absorption. This contributes to achieving the optimal reverberation time values as stipulated by some regulations [57].

4.2.3 Thermal regulation

Research indicates that vertical green systems offer substantial benefits in mitigating solar radiation, lowering surface temperatures, minimizing interior temperature fluctuations [58], and reducing energy cost [59].

4.3 Psychological and well-being benefits

4.3.1 Improved mental health

The restorative features of vegetated buildings improve mental health. Exposure to greenery reduces stress, anxiety, and mental fatigue, enhancing overall well-being [6].

4.3.2 Increased productivity

Vegetated spaces in workplaces improve concentration, cognitive function, and employee performance. Furthermore, plants in classrooms increase productivity [60].

4.3.3 Enhanced esthetic appeal

Improving the visual quality of building facades while incorporating citizens' visual preferences contributes to sustainable urban development. This approach not only enhances the esthetic appeal of the built environment but also fosters a sense of belonging and increases social satisfaction among urban residents [61].

4.4 Economic and property value benefits

Buildings with green infrastructure are more attractive to buyers and tenants, leading to higher market values [7].

5. Disadvantages and challenges

5.1 High initial costs

Installation expenses, specialized materials, and professional expertise contribute to the high initial costs. The structural reinforcements, specialized irrigation systems, and waterproofing layers required for vegetated systems increase construction costs. High-quality substrates, geotextiles, and support structures add to the financial burden of implementation. Additionally, designing and installing green systems necessitate specialized knowledge, increasing consultation and labor costs [8].

5.2 Structural and load-bearing challenges

Green roofs and vertical gardens add significant weight to buildings, potentially requiring reinforced structures to support the additional load. If installed incorrectly, excess moisture retention and root penetration can lead to water leakage, deterioration of building materials, and damage to structural components [8].

5.3 Maintenance challenges and operating costs

The maintenance of green roofs presents a significant challenge for building owners, often causing uncertainty regarding their long-term upkeep. Green roofs require regular irrigation, particularly in drought-prone climates, as well as periodic fertilization, which can inadvertently promote weed growth. Consequently, frequent maintenance inspections are necessary to ensure optimal plant health and system functionality. To reduce irrigation frequency, plant selection is often restricted to drought-resistant species, primarily succulents [9].

One of the critical concerns associated with green roofs is the potential for water leakage. Since the substrate is frequently in a saturated state, effective waterproofing and leakage protection are essential to prevent structural damage and ensure building longevity [9].

The maintenance requirements of a green roof largely depend on its type. Extensive green roofs generally require minimal upkeep, including plant protection, drainage inspections, and weed removal. In contrast, intensive green roofs demand more detailed and labor-intensive maintenance activities due to their higher plant diversity and complex irrigation systems. Regardless of the green roof type, weed management remains a major and time-consuming aspect of maintenance [9].

Green walls and roofs need continuous care and knowledge to maintain properly; implementing sustainable methods in the building enterprises becomes difficult because there is a shortage of skilled workers about sustainable construction. Some places in Africa do not have enough resources or trained workers for maintenance of the vegetation that has been integrated into urban design, which over time could cause the vegetation to deteriorate when not well maintained [12, 14].

Another issue could be high energy cost, for example, the Pasona Urban Farm (Tokyo, Japan). This corporate building features a green atrium with indoor farming, but the energy demands for artificial lighting and climate control could undermine its sustainability [62].

5.4 Lack of local research

Research on the performance of green roofs remains largely localized, resulting in a significant knowledge gap that hinders their widespread adoption. Current studies on green roofs are predominantly concentrated in a limited number of countries across Europe, North America, and Asia, leaving many other regions without sufficient data or guidelines for implementation. As a result, countries outside these research hubs often rely on imported green roof components, which can lead to high costs and potential failure due to inadequate adaptation to local climatic conditions [9].

Given that each country exhibits unique climatic characteristics and patterns of urbanization, conducting region-specific research is essential for ensuring the success of green roof systems. The development of growth mediums using locally available materials and the selection of native plant species are crucial factors in enhancing the effectiveness, sustainability, and long-term viability of green roofs in diverse geographic contexts [9].

5.5 Water management and drainage issues

Inadequate waterproofing layers can cause seepage, leading to moisture-related issues inside buildings. Furthermore, poorly designed irrigation systems can result in excessive runoff, waterlogging, or inefficient water use. Additionally, prolonged moisture retention on facades or green walls can lead to mold, mildew, and algae formation, compromising air quality and structural integrity [63].

5.6 Plant selection limitation

Not all plant species are suitable for extreme weather conditions in urban settings, restricting the range of vegetation that can thrive in harsh climates. The plant selection should also be limited to the indigenous plants of an area to avoid invasive species. Furthermore, the plant selection determines the water demand, which can be a separate problem. Additionally, certain plants can also cause a problematic pollen production [10].

5.7 Pests and diseases

Green systems can attract insects, rodents, and plant diseases, requiring constant monitoring and management [11, 12].

5.8 Complex irrigation systems

Green roofs and green facades require complex irrigation systems due to several factors, including limited soil depth, water retention challenges, exposure to harsh environmental conditions, and plant diversity. Unlike traditional gardens, these vegetated systems are installed on vertical or elevated surfaces, making natural water infiltration and distribution more difficult [64, 65].

5.9 Water demand

Due to harsh conditions and heat radiation from surroundings, there is a water demand that needs to be addressed to keep the green system live. On the other hand, indoor living walls or pockets have no access to rainwater and therefore needs to be supplemented [66].

5.10 Fire hazard

Green systems can cause fire hazards if not properly designed, maintained, and monitored. The risk primarily arises from dry vegetation, inadequate firebreaks, flammable plant materials, and external ignition sources [13].

5.11 Climate viability

One of the key challenges governments encounter when incorporating vegetation into urban design is ensuring climate viability. This challenge is particularly pronounced in Africa, which encompasses a wide range of climatic conditions, including tropical rainforests, arid deserts, and semi-arid regions. Selecting appropriate plant species that can withstand extreme weather conditions, such as prolonged droughts or heavy rainfall, while also thriving in the local climate is essential yet complex. Careful consideration of native and adaptive plant species is crucial to ensuring the long-term success and sustainability of urban vegetation integration [67].

6. Examples of failed or problematic greenery installations

While green infrastructure offers numerous environmental and esthetic benefits, several high-profile failures highlight the challenges associated with its implementation. Structural issues, poor drainage, erosion, and inadequate maintenance have led to significant problems in various projects worldwide.

6.1 Extensive green roof collapse (St. Charles, Illinois, USA)

One of the most notable failures involving rooftop structures occurred in St. Charles, Illinois. This project, designed to be the largest sloped green roof in the United States, suffered a catastrophic collapse during a heavy snowstorm. Although no injuries were reported, the structural damage was severe.

The primary cause of the collapse was inadequate drainage. Since snow is essentially frozen water, areas where water tends to accumulate on a roof are also more likely to experience excessive snow buildup. The failure was likely due to an insufficient or clogged drainage system combined with an ineffective growing medium, which resulted in water and snow retention. The additional weight imposed by these factors, particularly during an extreme winter event, exceeded the roof's structural capacity, ultimately leading to its failure [68].

6.2 Pine Creek wastewater treatment facility (Calgary, Canada)

The Pine Creek Wastewater Treatment facility had an extensive green roof; however, due to wind and water erosion, the green roof was damaged [69].

6.3 Paradise Park Children's Centre (London, UK)

One of the United Kingdom's earliest living wall installations experienced significant failure within a short period. Upon its completion in 2006, the DSDHA-designed Children's Centre in Islington featured a vibrant vertical garden comprising over 30 plant species. However, within three years, the £100,000 installation had deteriorated, leaving behind an unsightly array of dried, brown roots. Rather than allocating additional public funds to restore the living wall, the local council chose to introduce trailing plants as an alternative, though this approach yielded only limited success [70].

6.4 Westfield Warringah mall (Sydney, Australia)

In 2016, a hybrid vertical garden at Westfield Warringah in Brookvale, Sydney, was developed. Stainless-steel cables and mesh were installed to support specialized garden panels, which were installed on 14 vertical columns within the central area of the complex. The specialists were responsible for maintenance during the initial 12-month period as per the agreed contract. However, following this period, the maintenance contract was reassigned to another company that lacked specialized expertise in vertical garden management. Subsequent observations by the specialists revealed significant deterioration of the columns, suggesting that minimal maintenance or fertilization had been carried out in the year following their contracted maintenance period. As a result, up to 60% of the columns required replanting, with some necessitating complete replacement using pre-grown panels [71]. This case underscores the importance of continuous expert maintenance for vertical gardens. It also serves as a critical reminder that green facades require ongoing care and cannot simply be treated as "set and forget" installations.

7. Conclusion

In conclusion, biophilia and biophilic design underscore the fundamental human connection with nature and highlight the importance of integrating natural elements into the built environment. By incorporating vegetation through horizontal green spaces, vertical green spaces, and three-dimensional green pockets, architects and urban planners can create healthier, more sustainable, and esthetically pleasing spaces. While these green installations provide numerous ecological and psychological benefits, their success depends on thoughtful design, proper maintenance, and a clear understanding of their functional purposes. As cities continue to grow, embracing biophilic design will be essential in fostering urban resilience, enhancing biodiversity, and improving overall well-being for future generations.

Incorporating vegetation into building design presents a multifaceted approach to enhancing urban sustainability and offering numerous environmental, physical, psychological, and economic benefits. Green infrastructure contributes to improved microclimates, air quality, and stormwater management while promoting biodiversity and urban reconciliation ecology. Additionally, it enhances physical and mental well-being, reduces noise pollution, and provides economic advantages through increased property value and energy savings. However, these benefits come with notable challenges, including high installation and maintenance costs, structural and load-bearing concerns, complex irrigation systems, and climate adaptability issues. The lack of local research, resource availability, and skilled labor further complicates the widespread adoption of green systems, particularly in regions with extreme weather conditions. While the integration of vegetation into urban architecture presents a promising solution for sustainable urban development, addressing these challenges through innovative designs, policy support, and region-specific research is crucial for its long-term success.

The challenges and failures of various green infrastructure projects highlight the critical importance of proper planning, execution, and maintenance. While vegetation integration into buildings offers significant environmental and esthetic benefits, these cases demonstrate that neglecting key design considerations can lead to structural failures, erosion, plant deterioration, and financial losses. Factors such as inadequate drainage, insufficient structural reinforcement, lack of expert maintenance, and poor adaptation to local environmental conditions have contributed to the failure of several high-profile installations.

The following lessens were learnt: Green roofs and walls add additional weight to buildings, requiring thorough structural assessments to ensure load-bearing capacity, especially in regions with heavy snowfall or strong winds. Poor drainage can lead to water accumulation, increasing the risk of structural collapse, erosion, and plant mortality; therefore, proper waterproofing and water management strategies must be implemented. Additionally, green facades and roofs require specialized maintenance to remain healthy and functional. Assigning upkeep to unqualified teams can lead to rapid deterioration. Furthermore, the failure of the Paradise Park Children's Centre living wall emphasizes the need for plant selection based on climate suitability and sustainable upkeep practices. Ultimately, successful green infrastructure depends on integrating structural integrity, climate-appropriate plant selection, and a long-term maintenance strategy. By learning from past failures, future projects can be designed and managed more effectively, ensuring sustainable and resilient green building solutions.

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Section 2

Functional Approaches to Sustainable Built Environments

Chapter 5

From Fibers to Function: A Multilayered Textile System for Adaptive and Sustainable Architecture

Amirhossein Ahmadnia, Giuseppe Noventa and Alessandra Zanelli

Abstract

Textiles are highly valued in architecture for their lightweight, flexible, and adaptable qualities. However, materials like PVC-coated polyester, commonly used for waterproofing, pose environmental challenges, including poor breathability, condensation issues, and high environmental impact. This research proposes multilayered textiles as a sustainable alternative to PVC membranes. Made from recyclable or biodegradable materials, these fabrics balance high performance with reduced environmental impact. The multilayered system is designed at both the system and fiber levels, with each layer optimized for specific functions. Seamless layer connectivity ensures adaptability, reversibility, and compliance with design-for-disassembly principles, enhancing both performance and recyclability. Knitted textiles, as a subset of multilayered systems, provide exceptional opportunities for customization and sustainability. Computational knitting techniques enable precise control over global and local geometries, transitioning seamlessly from macro-scale structures to micro-level configurations. This integration of computational design and experimental validation addresses critical architectural challenges such as energy efficiency, dynamic adaptability, and material optimization. By presenting a replicable framework for designing sustainable textile systems, this research highlights the potential of multilayered textiles to redefine architectural membranes, offering lightweight, efficient, and environmentally responsible solutions for building applications.

Keywords: multilayered textiles, computational knitting, solar reflectance adaptation, material optimization, sustainable design

1. Introduction

Traditionally, textiles were employed as small-scale shelters, often constructed in the form of tents. The origins of textile structures date back over 44,000 years to the Ice Age on the Siberian Steppes. Archaeological findings have identified remains

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of these structures as "simple tent-like shelters" created by Mousterian cultures, who were Neanderthals living in the Middle Paleolithic period in Europe [1]. For centuries, textiles were primarily associated with temporary and emergency architecture due to their limited durability. However, advancements in architectural technology have made it possible to use textiles for large-scale structures, both temporary and permanent, with lifespans comparable to those of buildings constructed from much heavier materials [2, 3].

Textiles present unique advantages due to their lightweight nature, flexibility, and adaptability. Made from various fibers and yarns, textiles are highly customizable, enabling architects and designers to maximize their potential and create tailored solutions for different functions. The flexibility of textiles allows for easy reconfiguration, while their lightweight nature facilitates transport and installation without adding significant load to existing structures.

The twentieth century was pivotal in the advancement of textile architecture, largely due to breakthroughs in materials science and engineering [1]. In more recent decades, innovations such as synthetic fibers and new materials, including polyester, ETFE (Ethylene Tetrafluoroethylene), and PTFE-coated fiberglass, and the introduction of advanced computational design tools have further expanded the potential applications of textile structures. Visionary architects like Frei Otto spearheaded the use of tensile structures, which not only provided practical benefits like lightness and flexibility but also contributed to the esthetic appeal of modern architectural design [2].

When treated with appropriate finishes, they serve well as outdoor systems, typically using PVC-coated polyester for waterproofing. PVC is known for its durability, versatility, and low cost [4]. However, these materials present challenges, including poor breathability, leading to condensation [5]; significant environmental concerns related to the toxic life cycle of PVC; the use of non-renewable resources for production; and challenges associated with recycling, with only 3% recycled and 82% going to landfills [6].

The versatility and adaptation of textile materials are demonstrated by the development of textile architecture from basic shelters to intricate, multipurpose buildings. In order to strike a compromise between great performance and less environmental impact, this chapter explores the replacement of PVC with *multilayered textiles*.

2. Multilayered textile

A multilayered textile system is a purpose-built component composed of two or more distinct textile layers, designed to work together as a unique system for specific performance objectives. Each layer is computationally designed to address a particular task—such as providing structural support, thermal insulation, moisture control, or solar protection—based on the design requirements. These layers are engineered to interact synergistically, delivering enhanced functionality compared to single-layer textiles.

To ensure sustainability and adaptability, the layers can be connected in a way that facilitates secure disassembly, allowing for maintenance, replacement, or reusing. A key characteristic of this system is its ability to address multiple functionalities simultaneously, even when these functions align with or contradict one another. This makes multilayered textiles particularly valuable in applications where diverse and often competing demands must be integrated into a single, adaptable membrane solution. Additionally, these systems can be modular, enabling further customization and scalability.

2.1 Key features of multilayered textiles

In multilayered textiles, the integration of layers can be defined as a connection between different layers with no chemical connections but using techniques that either secure their separation or allow them to be located adjacent to one another without any permanent integration, meaning that they can be easily separated (like the integration of channels and bars in the knitted textiles [7]). This type of layer integration maintains the system's overall configuration, allowing for disassembly or replacement of individual layers, and supports design for adaptability. The system may include active or passive adaptability, such as shape-memory materials, dynamic reflectivity, or modular elements that respond to environmental changes.

Functional specification and material diversity are other key features of multilayered textiles. Each layer is optimized for a specific role; considering this fact, the type of fiber(s) to be used in each layer can be optimized and tailored for their intended functions.

The concept of a multilayered textile system can also be seen in ETFE cushion systems, which consist of two, three, or even four layers of ETFE foil [8]. Air must be constantly pumped into the chambers of the ETFE cushion since it is not airtight, requiring continuous monitoring and energy. Moreover, the foils provide a waterproofing function. However, the compacted air (air gaps) between the layers of ETFE, the addition of low-emissivity coatings, or the use of aerogels can improve the system's thermal performance [9], but these are not inherent features of the foil. In contrast, a multilayered textile system is expected to provide multiple functions inherently (based on the features of the selected fiber) within the system. Additionally, while multi-layer ETFE does not offer mechanical strength, the proposed multilayered system is designed to support its own weight and remain stable once installed.

2.2 Multilayered knitted textile

With the use of knitted textiles, which offer customization and waste reduction potential during the fabrication process [10], it becomes feasible not only to integrate multiple fibers into a single layer of textile but also to tailor, optimize, and customize each layer's pattern using data-driven design. Furthermore, each layer can be constructed from a collection of distinct patterns [11], enabling the design process to transition from global geometry to local geometry and even yarn-level design.

Computational knitting has deeply revolutionized various industries, including fashion, sports, and healthcare, by enabling the creation of complex three-dimensional fabrics in a quick and efficient manner. This advancement is attributed to the integration between knitting machines and specialized software, particularly in the medical and fashion fields. Despite some challenges, more brands are embracing automated knitting technologies, and there is growing potential for this technology in engineering and architecture, although research in these areas remains relatively limited [10].

Recent advancements, such as the Isoropia installation at the Venezia Biennale 2018, demonstrate the potential of pre-programmed computer numerical control (CNC) knit technology for lightweight and high-performing membranes. In this project, the knitting process was used to define specific tensioning lines within the fabric, resulting in a lightweight and high-performing membrane [12]. Moreover, some studies have tested fabrics with a piqué Lacoste loop structure under uniaxial and biaxial tension to evaluate their feasibility for large-scale architectural applications [13].

This multilayered knit approach has already been explored in the fashion industry, where layers are used to separate certain fibers from the skin to enhance the overall performance of textiles [14]. However, the implementation of a single fabric composed of multiple knit layers to achieve diverse performance characteristics within architectural applications represents a significant innovation. By integrating these functionalities into a single installation, this approach pushes the boundaries of what knitted textiles can achieve in sustainable and adaptive architecture.

The next step in the evolution of knitted membranes involves not only optimizing their performance but also addressing their sustainability. To achieve this, different performance attributes of a knitted membrane—such as acoustics, thermal insulation, optical properties, and humidity control—can be assigned to various layers within a multilayered textile.

3. Sustainability aspects of multilayered textiles

The concept of multilayered textiles allows for the creation of membranes that can be fully disassembled at the end of their lifecycle, enabling the separation of mono-material layers for complete recyclability.

Although textiles generally have a less negative environmental impact compared to traditional materials used in the construction sector—due to their lightweight nature and the minimized use of resources and energy during production—they are not inherently sustainable [10]. Theoretically, some membranes, such as ETFE foils, are fully recyclable [10], while other fiber-reinforced thermoplastic polymers (FRTPs), such as carbon fiber or glass fiber-reinforced thermoplastics, are designed to be recyclable (need reference). However, recycling these materials often requires significant energy input, and their mechanical properties can degrade substantially during the process [15, 16]. Furthermore, the recycling of fluoropolymers can release toxic gases, raising concerns about the environmental safety of these processes. Membranes such as PVC-coated polyester are only partially recyclable, and most textiles in the fashion and construction sectors still end up in landfills at the end of their lifecycle [10].

According to Ref. [17], fiber production, yarn spinning, and fabric production are the most polluting stages in textile manufacturing. The concept of multilayered knitted textiles, fabricated using modern computer numerical control (CNC) machines, can address these challenges by minimizing waste during the fabrication process. A design-for-disassembly approach enables the recovery and reuse of individual layers, while the mono-materiality of each knitted layer facilitates reversibility and the efficient recovery of fibers, effectively closing the material loop. It is important to note that knitted textiles also allow for the integration of different types of fibers within a single knitted layer. Since the connections between fibers in a knitted layer are formed through fiber loops rather than chemical bonds, even multi-fiber knitted layers can maintain reversibility, enabling efficient disassembly and recycling.

Although the most common types of membranes and textiles in the construction sector are derived from synthetic resources produced by non-renewable sources, multilayered knitted textiles offer the flexibility to integrate not only synthetic yarns but also natural and bio-based fibers. This versatility in material selection significantly broadens the range of sustainable options, enabling the development of systems that combine performance with environmental responsibility.

Additionally, computational design can optimize the density and distribution of fibers within each layer, reducing material consumption and promoting efficient use of resources. This process not only enhances the potential of textiles as lightweight and multi-functional systems at the building scale but also supports the creation of reversible and sustainable components.

While the concept of multilayered textiles addresses the challenges of sustainability and adaptability, translating these ideas into practical architectural applications requires innovative approaches. The next section explores how advancements in textile systems have paved the way for experimental prototypes.

4. Design methodology

To realize the potential of multilayered textile systems, a robust and performance-driven design methodology is essential. This section explores the computational tools and processes that form the foundation of this research, emphasizing their role in optimizing both global and local design levels.

The proposed design methodology consists of two interconnected levels, forming a looped workflow that relies entirely on performative and environmental data as inputs. These levels work synergistically, with data informing both macro-level (global) and micro-level (local) decisions to ensure that the system responds effectively to its context and functional requirements. To illustrate the methodology and clarify the relationship between these levels, this chapter utilizes a case study, demonstrating the importance of real-world input data in computational design workflows.

4.1 Case study: Multilayered knitted textile for solar reflectance adaptation

Traditional façade systems predominantly rely on static designs that are not capable of adapting to changing environmental conditions. This research introduces an innovative adaptive Solar Reflectance Adaptation (SRA) system specifically tailored for the opaque portions of building envelopes. The core innovation of this system lies in its ability to dynamically adjust its reflective and absorptive properties, optimizing solar heat gain and loss in response to varying seasonal demands.

Conventional systems often focus on reducing the U-value, a material-dependent factor that can inadvertently increase the overall weight of the system. This added weight may impose additional loads on older structures, which were not originally designed to support such burdens. Therefore, it is essential for the designed system to remain lightweight, ensuring compatibility with existing buildings.

Building on the concepts discussed in the previous sections, this chapter considers a multilayered textile system designed for solar reflectance adaptation as a case study. The following design levels investigate the general workflow proposed for designing multilayered textiles while going deeper into the design of this specific system to provide a better understanding.

4.2 Macro-level design

This level of design focuses on the computational design and optimization of the global geometry of the Solar Reflectance Adaptation (SRA) system. The development and presentation of a workflow, which includes analysis, simulation, and optimization processes, ensures the efficiency and functionality of the system based on input variables. This workflow, defined as a performance validation loop, computationally assesses and validates the system's performance through energy, structural, and environmental simulations.

The macro-level design investigates the shape and configuration of the multilayered textile system. Before delving into this level of design, conceptual considerations regarding the initial number of layers and the methods of connecting them are important. Considering the defined functions and requirements for the case study, two primary scenarios are identified:

- *Summer scenario*: The system must reflect solar radiation, necessitating a reflective layer.

- *Winter scenario*: The system must absorb solar radiation, requiring an absorptive layer.

While these two functions are the most crucial, additional functionalities such as structural support, hygroscopic behavior, or transmittance can be integrated as needed by the designer. The primary sketch of the layers and their configuration is shown in **Figure 1**. The layers are as follows:

- *Outer (external) layer*: This layer serves as the esthetic covering and is primarily responsible for transmitting the maximum amount of solar radiation into the system for further management by the inner layers.

- *Middle (filler) layer*: This layer reflects solar radiation during the summer scenario and manages the system's configuration changes, switching its functionality.

- *Inner layer*: Activated during the winter scenario, this layer absorbs solar radiation. It is coated with a suitable material to enable a double skin facade (DSF) behind it.

To run the parametric algorithm and optimization process, certain design variables must be defined according to the system's configuration. Since the case study presents dual functionality, it requires two configurations or sets of parameters

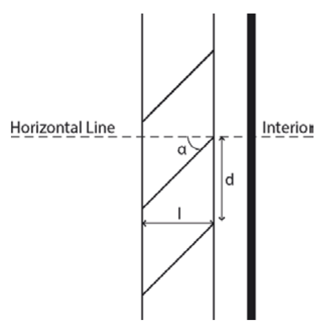

Figure 1.
A section of the configuration and parameters of the designed system.

Symbol	Variables	Domain
α	Angle of the filler layer with the horizon line (Summer Scenario)	$-90 < X < 90$
α	Angle of the filler layer with the horizon line (Winter Scenario)	$-90 < X < 90$
d	Distance between two consecutive filler layers	$0 < X$
l	Length of filler layer	$0 < X$

Table 1.
Table of design space variables.

optimized for both scenarios. The middle layer, playing a critical role in changing the system's configuration, has a parameter (α) that must be optimized separately for each function. Other parameters can be optimized once, based on one scenario. The design variables are listed in **Table 1**.

After defining the design variables, the objective functions and fitness functions must be tailored to meet the specific needs and requirements of the system. In this case study, ray tracing analysis is employed as the primary evaluation method to optimize the solar design. This analysis plays a critical role in enhancing the system's ability to manage solar radiation. By simulating the interaction of sunlight with the façade surface, ray tracing determines the most effective configuration for reflecting or absorbing solar energy.

The optimization of system parameters requires defining specific objective functions for both winter and summer scenarios, ensuring optimal year-round performance. In the winter scenario, the primary objective is to maximize the passage of sunlight through the system while minimizing reflection. This configuration allows the system to absorb the maximum amount of solar radiation, thereby reducing the heating load on the building. The system must be designed to capture as much beneficial solar radiation as possible during the colder months.

Conversely, in the summer scenario, the goal shifts to maximizing the reflection of sunlight by the filler layer. This helps minimize the cooling load by reducing excessive solar heat gain. It is crucial that the reflected solar radiation is directed back into the atmosphere rather than onto the surrounding urban environment to mitigate the Urban Heat Island (UHI) effect. These objective functions ensure that the system adapts dynamically and maintains effective performance across varying conditions, ultimately improving the building's energy efficiency throughout the year. **Table 2** presents the objective functions per action, and **Figure 2** presents the geometrical method of measuring the objectives.

To conclude the macro-level design process (global geometry), a final validation check is recommended. The purpose of this check is to ensure the feasibility and effectiveness of the designed system before proceeding to the micro-level design. This validation can be achieved through simulations based on the system's objectives. In this case study, where the primary goal is to reduce the thermal loads of an existing building, an energy simulation can be conducted. By comparing the results before and after the system's application, the efficiency of the design can be demonstrated. The results show that installing the SRA system on the southern part of the façade of the existing building in Milan, integrated with an open cavity during summer, can reduce the cooling load by 57% on June 21st at 12:00 PM. Additionally, with a closed cavity configuration in winter, the system can achieve a 20% reduction in heating load.

Objective	Metric (condition; unit)	Evaluation method
Max absorption of sun radiation (winter)	Min reflectance of sun rays by filler layer; percentage	Ray tracing
Max reflectance (summer)	Max reflectance of sun rays by filler layer; percentage	Ray tracing
Reduce the UHI (summer)	Min sun rays reflected to the urban area; percentage	Ray tracing
Area of the filler layer (summer)	Min area; square meter	Geometrical calculation

Table 2.
Objective function assumptions.

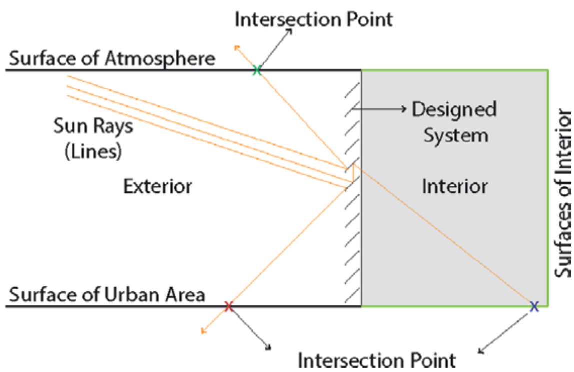

Figure 2.
A diagram presenting the geometrical measurements of the objectives.

The macro-level design process can be divided into three main steps:

- Defining the system's shape and configuration by setting design variables (parameters).
- Optimizing the parameters based on the defined objectives and fitness functions.
- Performing a simulation-based validation check.

For the defined case study, environmental data play a critical role in both the optimization and simulation steps. **Figure 3** illustrates the final global geometry of the case study for both scenarios.

4.3 Micro-level design

Textiles offer a unique opportunity for customization, particularly in their patterns and the types of fibers used—collectively referred to as the "local geometry." This high degree of customizability allows for the optimization of materials to meet specific functional and environmental requirements, thereby reducing embedded carbon, costs, and resource demands.

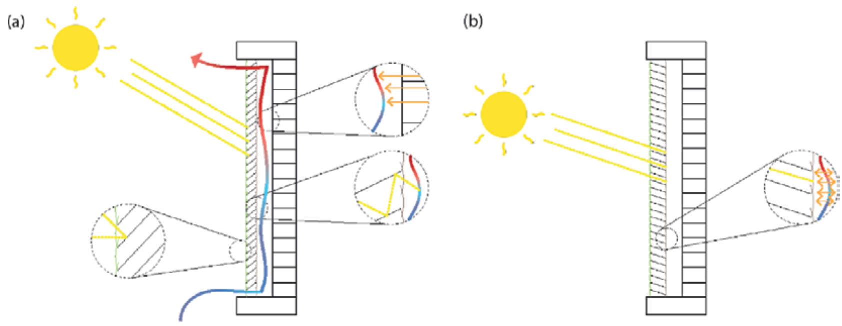

Figure 3.
Conceptual scheme of the system: (a) Summer scenario, (b) Winter scenario.

At the micro-level, this design approach leverages the potential of textiles as materials composed of numerous interconnected patterns, each of which can be tailored in shape (e.g., to achieve varying levels of porosity) and material properties (e.g., by selecting specific fibers). This customization process is informed by data-driven design methodologies that aim to maximize both performance and sustainability. By tailoring patterns and fiber characteristics to match precise functional needs, this approach not only enhances the efficiency of the system but also minimizes resource use and environmental impact.

An overview of the pattern-informed design approach workflow is presented in **Figure 4**. This methodology can be applied to various design scenarios and is structured around three key steps:

- *Properties data set:* The first step involves conducting experimental tests and collecting data on selected materials and patterns to build a numerical dataset. This dataset can include different parameters such as mechanical properties, hygroscopic properties, reflectance/absorptance coefficients, transmittance coefficients, weight per unit length of fiber, environmental impact (e.g., carbon embedded, etc.), cost, and others. While some parameters, like reflectance and absorptance coefficients, are intrinsic to the material, others, such as transmittance, are influenced by the specific pattern. This step provides a comprehensive understanding of the physical, optical, and environmental properties of the design components, forming the foundation for subsequent optimization.

- *Catalog of textiles:* Based on the parameters established in the first step, a catalog of textiles is generated. This catalog encompasses a wide range of combinations between different fiber types and patterns, offering a versatile database for design applications. The catalog supports the selection of textiles tailored to various functional and environmental requirements, ensuring adaptability to different design contexts.

- *Match-Making Algorithm:* The final step employs an optimization algorithm, such as NSGA-II, to determine the most suitable textile configuration for the design objectives. The algorithm can accommodate a range of objectives, including maximizing reflectance, minimizing weight, reducing costs, or lowering environmental impact. By weighting these objectives based on project-specific priorities, the optimization process ensures the system's performance aligns with its intended purpose.

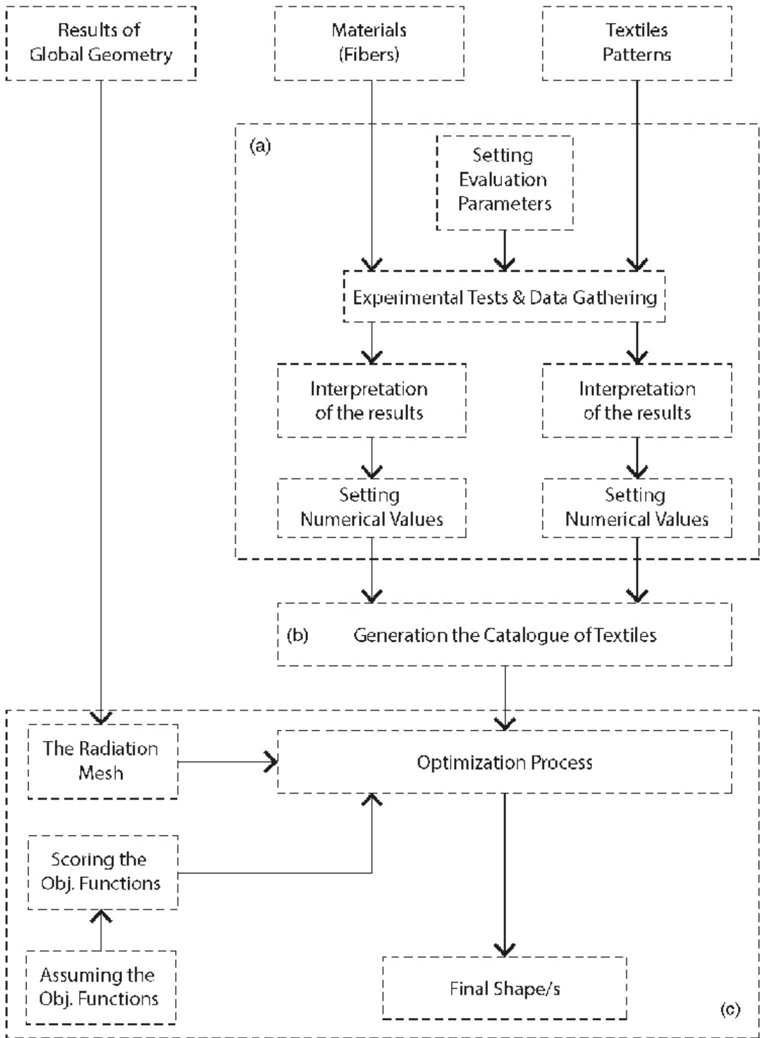

Figure 4.
An overview of workflow: (a) Data set creation, (b) Catalog of textiles, (c) Match-Making Algorithm.

For the defined case study, this workflow is tailored to optimize the Solar Reflectance Adaptation (SRA) system described in the previous sections. The properties dataset includes detailed measurements of reflectance, absorptance coefficients, and transmittance values for materials and patterns designed to enhance solar energy management. These evaluation parameters can be experimentally tested to ensure accuracy and reliability, providing a robust foundation for the subsequent optimization process.

The reflectance test aimed to determine the reflectance and absorptance coefficients of the selected fibers, which are considered opaque materials. A total of 10 fibers were tested using a UV/VIS/NIR spectrometer (PerkinElmer Lambda 950) equipped with a 150 mm InGaAs integrating sphere. Measurements followed the BS EN 410:2011 standard, typically used for glazing materials, covering a wavelength range of 200–2500 nm at 5 nm intervals to capture the full solar spectrum.

Two methods were employed: testing the raw fibers in their unprocessed state (**Figure 5a**) and testing the fibers after being knitted into a fabric, folding it several times to remove transmittance (**Figure 5b**). The result of this test can be seen in **Table 3** and **Figure 6**.

Transmittance is a critical optical property, particularly for materials that are transparent or semi-transparent. Since this research focuses on textiles that are not completely opaque, conducting transmittance tests is essential. Unlike reflectance tests, which are performed on fibers alone, transmittance tests must be conducted on the entire textile, as the transmittance value is significantly influenced by the specific textile pattern.

For knitted textiles, the complexity increases due to pre-tensioning forces that alter the configuration of the pattern. These forces can lead to variations in

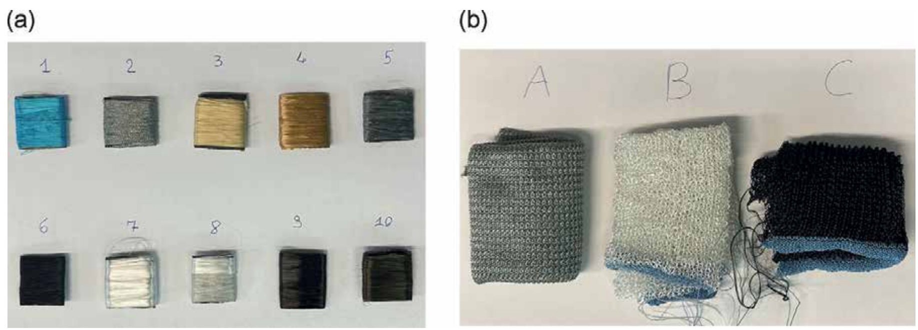

Figure 5.
Reflectance test: (a) Raw fiber, (b) Folded piece of knitted textile.

Sample code	Fiber name	Solar reflectance (%)	Visible solar reflectance (%)
Sample 1	Recycled PET - Blue	39	24
Sample 2	Fireproof Polyester	26	23
Sample 3	Technora	52	42
Sample 4	Zylon	42	27
Sample 5	Recycled PET - Gray	22	17
Sample 6	Recycled PET - Black	3	3
Sample 7	Glass Fiber	70	73
Sample 8	Recycled PET - White	52	51
Sample 9	Carbon Fiber	8	6
Sample 10	Basalt	12	8
Sample A[a]	Fireproof Polyester	29	22
Sample B[b]	Recycled PET - White	60	56
Sample C[c]	Recycled PET - Black	1	1

[a]*A is Compatible with sample 2.*
[b]*B is Compatible with sample 8.*
[c]*C is Compatible with sample 6.*

Table 3.
Solar reflectance and visible reflectance data of fibers.

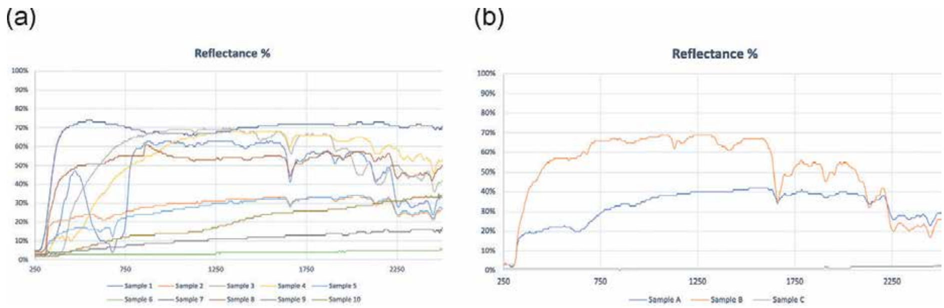

Figure 6.
The result of reflectance tests: (a) Raw fiber, (b) Folded piece of knitted textile.

transmittance based on the amount of tension applied and the specific behavior of different fibers under tension.

Given the high costs and challenges of testing all possible patterns under various tensioning conditions, this research proposes a streamlined approach involving two methodologies. The first methodology, referred to as the filtering process, involves the following steps (**Figure 7**).

- Pre-tensioning the knitted textile and measuring the applied tension using sensors.
- Scanning the textile patterns with a standard printer or scanner.
- Importing the scanned images into Grasshopper, a computational design tool, for analysis.
- Using a custom-developed algorithm to calculate the proportion of white areas in the image, which correlates directly with the textile's transmittance.

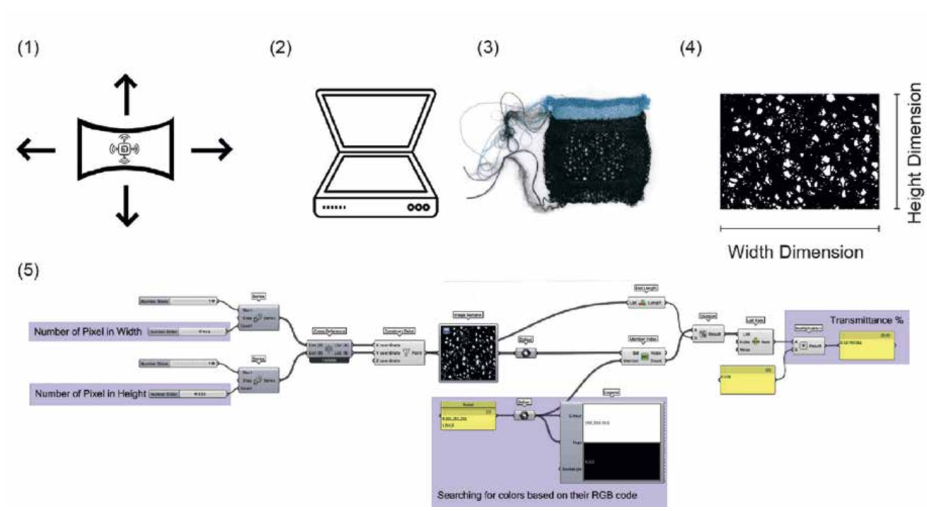

Figure 7.
Measuring the light transmission of the knitted sample: (1) Measuring the tension value of the sample by sensor, (2) Scanning the sample, (3) Scanned sample in the picture, (4) Applying the black and white filter and determining the dimension and pixels of the sample, and (5) Grasshopper algorithm for measurement.

The light transmittance $T_{textile}$ of a textile is calculated using the following formula:

$$T_{textile} = \frac{A_{white}}{A_{total}} \tag{1}$$

Where:

- $A_{white} = N_{white} \times A_{pixel}$: Total area of white regions in the scanned image.
- $A_{total} = N_{total} \times A_{pixel}$: Total area of the scanned image.

Once the best patterns have been identified through the filtering process, their transmittance properties can be measured more precisely using a rigorous methodology. This research adopts the methodology, standards, and equipment outlined by Zanelli et al. [18] to ensure accurate solar transmittance measurements. The transmittance properties of the filtered samples are evaluated with a spectral resolution of 5 nm across the range of 250–2500 nm, adhering to the ISO 90501 standard.

It is important to note that the relationship between transmittance (T), absorption (A), and reflectance (R) for each fiber and its compatible pattern can be expressed through the following equations:

$$1 = T_{textile} + A_{textile} + R_{textile} \tag{2}$$

$$R_{textile} = \left(1 - T_{textile}\right) \cdot \rho_s \tag{3}$$

$$A_{textile} = \left(1 - T_{textile}\right) \cdot \text{AbsorptionCoefficient} \tag{4}$$

Eq. (2) defines the fundamental balance between transmittance, absorption, and reflectance for textiles, where the sum of these properties equals 1. Eq. (3) expresses reflectance ($R_{textile}$) as a function of transmittance ($T_{textile}$) and the surface reflectance coefficient (ρ_s). Similarly, Eq. (4) defines absorption ($A_{textile}$) as a function of transmittance and the material's absorption coefficient. These equations form the basis for evaluating the optical performance of textiles within the defined design framework.

After finalizing the properties data set, a catalog of textiles is generated to establish a range of potential solutions. Given that not all fibers are compatible with every pattern, a compatibility matrix is employed to define permissible combinations of fibers and patterns. **Figure 8** illustrates an example of data storage and visualization for a textile catalog, featuring five distinct fiber types (recycled PET in various colors) and five patterns, each with differing levels of compatibility.

The primary objective of the match-making algorithm is to identify the optimal textile from the catalog for each face of the radiation mesh generated by the radiation study, ultimately producing a final textile configuration. **Figure 9** illustrates the radiation mesh for the summer and winter scenarios applied to the filler and inner layers. The filler layer is designed based on the radiation mesh corresponding to detrimental sun radiation (reflectance functionality), while the inner layer is designed according to the radiation mesh for beneficial sun radiation (absorptive functionality).

	Reflectance	Absorptance	Transmittance	Weight	Embedded_Carbon	AP	ADP
PET_Blue-Pattern1	0.326000	0.489000	0.1850	0.0068	0.027132	0.000014	0.32844
PET_Blue-Pattern2	0.372480	0.558720	0.0688	0.0093	0.037107	0.000019	0.44919
PET_Blue-Pattern3	0.380800	0.571200	0.0480	0.0100	0.039900	0.000020	0.48300
PET_Blue-Pattern4	0.356000	0.534000	0.1100	0.0079	0.031521	0.000016	0.38157
PET_Blue-Pattern5	0.347600	0.521400	0.1310	0.0075	0.029925	0.000015	0.36225
PET_Grey-Pattern1	0.179300	0.635700	0.1850	0.0068	0.027132	0.000014	0.32844
PET_Grey-Pattern2	0.204864	0.726336	0.0688	0.0093	0.037107	0.000019	0.44919
PET_Grey-Pattern3	0.209440	0.742560	0.0480	0.0100	0.039900	0.000020	0.48300
PET_Grey-Pattern4	0.195800	0.694200	0.1100	0.0079	0.031521	0.000016	0.38157
PET_Grey-Pattern5	0.191180	0.677820	0.1310	0.0075	0.029925	0.000015	0.36225
PET_Black-Pattern1	0.024450	0.790550	0.1850	0.0068	0.027132	0.000014	0.32844
PET_Black-Pattern2	0.027936	0.903264	0.0688	0.0093	0.037107	0.000019	0.44919
PET_Black-Pattern3	0.028560	0.923440	0.0480	0.0100	0.039900	0.000020	0.48300
PET_Black-Pattern4	0.026700	0.863300	0.1100	0.0079	0.031521	0.000016	0.38157
PET_Black-Pattern5	0.026070	0.842930	0.1310	0.0075	0.029925	0.000015	0.36225
PET_White-Pattern1	0.570500	0.244500	0.1850	0.0068	0.027132	0.000014	0.32844
PET_White-Pattern2	0.651840	0.279360	0.0688	0.0093	0.037107	0.000019	0.44919
PET_White-Pattern3	0.666400	0.285600	0.0480	0.0100	0.039900	0.000020	0.48300
PET_White-Pattern4	0.623000	0.267000	0.1100	0.0079	0.031521	0.000016	0.38157
PET_White-Pattern5	0.608300	0.260700	0.1310	0.0075	0.029925	0.000015	0.36225

Figure 8.
Example of a textile catalog with a compatibility matrix, showcasing combinations of five fiber types and five patterns. AP: Acidification Potential, ADP: Abiotic Depletion Potential.

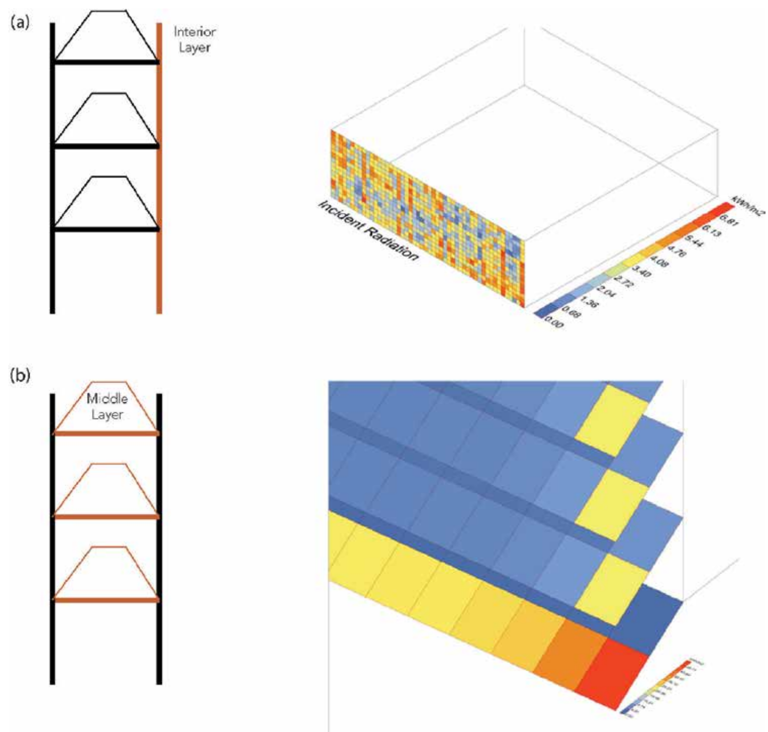

Figure 9.
Radiation mesh: (a) Winter scenario, (b) Summer scenario.

The radiation mesh reveals that some faces receive maximum solar radiation, indicating that the system must utilize its full potential to reflect or absorb solar energy in these areas. Conversely, other faces receive little to no solar radiation, meaning the system can operate with reduced functionality and material usage in those regions. This selective approach allows for material optimization and results in a more efficient and sustainable system. **Table 4** presents the assumed objective functions for both scenarios.

Objective	Metric (condition; unit)	Evaluation method
Max absorption of sun radiation (Absorptive textile)	Max absorption of sun radiation; percentage	Mathematical calculation
Max reflectance of sun radiation (Reflectance textile)	Min absorption of sun radiation; percentage	Mathematical calculation
Weight	Min weight of the designed textile; kg	Mathematical calculation
Carbon Footprint of the Final Solution	Min carbon embedded; $kgCO^2e$	Mathematical calculation

Table 4.
Objective function assumptions for the Match-Making process.

The micro-level design approach demonstrates the potential of textiles as fully customizable materials, enabling tailored solutions to meet specific functional and environmental requirements. By leveraging a data-driven methodology, this approach ensures the precise optimization of patterns, fibers, and material properties, enhancing the overall system's performance and sustainability.

While the macro-level design focuses on the global geometry and configuration of the multilayered textile system, the micro-level introduces a layer of granularity that enhances performance and resource efficiency. The integration of these two levels is achieved through a feedback loop where data from the micro-level informs and refines macro-level decisions and vice versa.

5. Conclusion

This chapter has demonstrated the potential of multilayered textiles as innovative, sustainable, and adaptive systems for architectural applications. By introducing a two-level design methodology, combining computational tools with experimental testing, this research provides a robust framework for designing and optimizing such systems. The case study of the Solar Reflectance Adaptation (SRA) system highlights the practical implementation of this methodology, showcasing its ability to dynamically respond to seasonal environmental conditions while minimizing resource use. Future research can build upon these findings by exploring additional material combinations, advancing computational modeling techniques, and validating these systems in diverse real-world contexts. Through these efforts, multilayered textiles can play a pivotal role in shaping the future of sustainable architecture.

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Chapter 6

Assessment of Lighting Intensity Utilizing DIALux Software: A Case Study of the FPSD Building at the Indonesian University of Education

Elih Mulyana Anisah

Abstract

Room lighting is the main issue for the functioning of a room. Educational buildings generally consist of various rooms such as classrooms, laboratories, and general rooms. These rooms have different lighting standards. This research is to determine the suitability of the lighting installation planning results with the lighting standards required in a building. Evaluate the lighting using DIALux software. The research method used was simulation using DIALux software; data installed in the field was tested with this software. The results of this research show as follows: in the planning data, it is known that the lighting intensity in classrooms is 377.37 lux, laboratories 353.27 lux, and corridors 127.97 lux, as well as light intensity that does not meet the standards, namely public spaces 231.17 lux. Meanwhile, the lighting intensity using DIALux software, 279 lux for classrooms, 413 lux for laboratories, 288 lux for public rooms, and 142 lux for corridors, meets the standards.

Keywords: education building, lighting, Lux, design, DIALux

1. Introduction

Lighting in educational buildings is a major part of running activities. A person will be able to run it comfortably if they use a good lighting system. Related to this, the lighting system in a building requires good planning in accordance with established standards.

Educational buildings have various rooms, such as classrooms, laboratories, and corridors, as well as various public spaces such as toilets, prayer rooms, meeting rooms, and so on. These educational rooms certainly have different functions in meeting the needs of educational facilities; therefore, different lighting is required.

Fulfillment of room lighting needs in educational buildings is regulated in the SNI 03–6575-2001 standard. The minimum light strength standard for classrooms is 250 lux, laboratories 350 lux, corridors 100 lux, and public spaces 250 lux [1]. An educational room is said to comply with SNI standards if the light strength, electrical power, and number of light points in the room are met correctly. Lighting that is less than specified, for example, in a classroom, if the light is less than 250 lux, people in the room will be uncomfortable and easily sleepy; conversely, if the light exceeds the standard, it will be dazzling for the user. There are many other activities related to lighting systems in multi-story buildings or other areas.

The planning of the lighting system for the Education Building was carried out by a planning consultant, and then the construction was carried out by a different contractor. In the implementation of development, errors often occur between the lighting plan and the construction of the lighting system.

On the other hand, determining the type of lamp is more than one product, with different prices. Different types of lamps will affect the lighting system in the room. So researchers feel it is important to evaluate building lighting needs in accordance with existing standards in Indonesia.

DIALux software is an application used to test and install lighting systems that have been installed in the field. The features in the software include visuals or displays of the type of lighting, light distribution, lighting lux value, position of light points, and the number of light points tested in a room [2].

2. Literature review

2.1 Lighting lamps

Lighting lamps are tools that function as artificial lighting [3]. Several things need to be considered when choosing the type of lamp that will be used in a particular room; these factors include the effectiveness of the light, color of the lamp, spectral range, and type of lamp [4].

The efficacy of lighting in a room is the source of light emitted and is related to the electrical power used. The efficacy value is expressed in lumen/watt units, where the total light flux is divided by the lamp light [5].

Apart from that, the lighting system is related to lamp depreciation or lamp life. You can find out by looking at the datasheet from the lamp manufacturer. The depreciation value of the lamp is influenced by changes in electric voltage, type of auxiliary components, and room temperature [6]. In the light spectrum, there are two factors that need to be considered, namely the visible color and the color-producing index. It is necessary to pay attention to the selection of lamp colors so that the lighting obtained is as required [6].

There are various types of lamps, including incandescent lamps and gas-discharge lamps [3]. Incandescent lamps are basically light bulbs consisting of gas and fine wire made from metal. Fluorescent lamps (tube lamps) are lamps that utilize fluorescent gas energy as a light emitter when there is an electric current [7, 8].

2.2 Armature

An armature is a device that functions to distribute the light emitted by the lamp installed in it [6]. The armature is equipped with light protection and control equipment [1]. Factors that need to be considered in selecting an armature are light efficiency, usage coefficient, light intensity distribution, armature classification based on the direction of distribution, and based on the installation method.

2.3 Light spreading

The form of light distribution can be seen from the type of armature used. The light source in the room is obtained from lamps, which are the primary light source, and secondary light sources, namely those that come from reflected objects of light fixtures and walls of the room [9]. There are several types of light distribution, including indirect lighting, semi-indirect lighting, general diffuse lighting, semi-direct lighting, and direct lighting.

2.4 Lighting intensity

The illumination intensity is the light flux that falls on a certain area. The unit of lighting intensity is lux with the symbol E. 1 lux = 1 lumen/m^2 [10]. Illumination (E) is directly proportional to the light intensity (I) of the source. A surface is inversely proportional to the square of the surface's distance from the source.

The lighting intensity equation is expressed as follows:

$$E = \frac{\Phi}{A}\left(lm / m^2\right) \tag{1}$$

Keterangan:
E = Lighting intensity (lux)
Φ = Luminous flux (lumen)
A = Intensity area (m^2)

2.5 Luminous flux

Luminous flux, or luminous current, is the amount of light emitted from a light source per second (s). The unit of light flux is lumen (lm) [9].

The luminous flux equation is expressed as follows:

$$\Phi = \mathrm{W} \times Lw \tag{2}$$

Keterangan:
Φ = Luminous flux (lumen)
W = Power (watt)
Lw = Lumen per watt (lumen/watt)

2.6 Minimum light recommendations

There are several sources that provide recommendations for minimum lighting levels in various rooms; the following data on recommendations for standards light intensity is available in SNI 03–6575-2001 (**Table 1**) [1].

2.7 DIALux

DIALux is software created by the DIAL company (Deutsches Institut fur Angewandte Lichttechnik), a company located in Ludenscheid, Germany. The DIALux

No.	Room Function	Lighting Level (lux)	Color Reduction Group
1	Classroom	250	1 or 2
2	Library	300	1 or 2
3	Laboratory	350	1
4	Design room	750	1
5	Food court	200	1
6	Computer lab	500	1 or 2
7	Corridor	100	1
8	Mosque	200	1 or 2
9	Toilet	250	1 or 2
10	Archive room	150	or 4

Table 1.
Minimum light Rekomenationi.

application has the function of designing lighting with a 3D (three-dimensional) appearance, as well as calculating lighting level results based on the input target [2].

3. Method

This paper is the result of research conducted with steps as shown in the flowchart in **Figure 1**.

3.1 Literature study

The literature study method was carried out to obtain library data as insight to be able to develop the research carried out relating to light intensity and apply DIALux software as a means of visualizing the lighting of an area.

3.2 Field study

The field study method was carried out to collect lighting data for each room of the FPSD building, including planning light intensity, the number of planning light points, and the area of each room.

3.3 Visualize DIALux

Then the lighting intensity design was carried out using DIALux software. This was done to obtain a 3D (three-dimensional) visualization of lighting planning in accordance with standards, and then it could be used as a comparison for company planning data.

3.4 Data analysis

After obtaining the visualization results, an analysis of the suitability of the building planning light intensity and the DIALux results was carried out with the SNI minimum light intensity standards.

Figure 1.
Research flowchart.

3.5 Conclusion

Lighting data compiled by the planners for the FPSD Building's lighting intensity requirements are as follows: classrooms 377.37 lux, laboratories 353.27 lux, and corridors 127.97 lux. Public spaces (restrooms, prayer room, archives, lecturer's room) 231.17 lux.

Meanwhile, an evaluation using DIALux software for the building revealed the lighting requirements for each room: classrooms 279 lux, laboratories 413 lux, corridors 142 lux, and public spaces 288 lux.

The comparison of the building's lighting requirements between the planning and calculations using DIALux software revealed differences.

Classrooms, corridors, and public spaces had lighting requirements above standard, while laboratories did not meet the required lighting standards.

4. Results and discussion

4.1 Lighting installation planning data

Lighting in the FPSD building uses Philips TL 2x18 Watt and Philips DL 16 Watt. The following is data on planning the lighting installation for the FPSD building (**Table 2**).

NO	Room name	Space room	Number of lights	Lux	Lumen
1	Classroom	10 x 7.1 m	12	377,37	26.880
2	Laboratory	9 x 8.4 m	12	353,27	26.880
3	Common room	5.5 x 3.45 m	2	231,17	4.480
4	Corridor	15.5 x 2 m	8	127,97	639,86

Table 2.
Lighting installation planning data in the FPSD building. Source: (Field lighting planning data).

4.2 DIALux software design results

The following are the results of the design of the room lighting installation in the FPSD building. The design was carried out by adjusting the minimum light intensity standards based on SNI 03–6575-2001. In the design of classrooms, laboratories, and public spaces, Philips TL 2x18 Watt lamps are used, and in the corridors, Philips DL 16 Watt lamps are used. So the results obtained are the number of light points that suit the needs of each room, the strength of the light current, the average light per square meter (lux), and the light distribution.

4.2.1 Classroom

There are 15 classrooms on seven floors of the FPSD building with the same shape and room area. The following is a visualization of the placement of the light points, the distance between the lights, and the appearance of the light distribution (**Figures 2** and **3**).

From the measurement results, it was stated that 16 light points were needed with a horizontal distance between lights of 2.5 m and a vertical distance of 1.775 m, a light intensity (flux) of 19,809 lumens, and an average per square meter of 279 lux with the target or SNI standard of 250 lux.

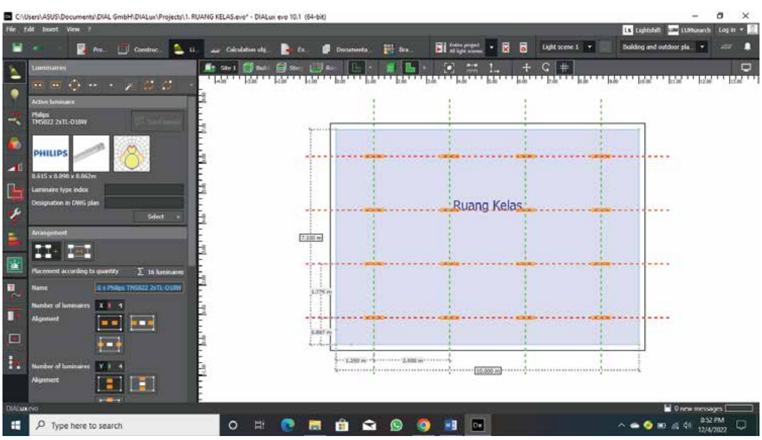

Figure 2.
Placement of classroom light points. Source: (DIAlux software).

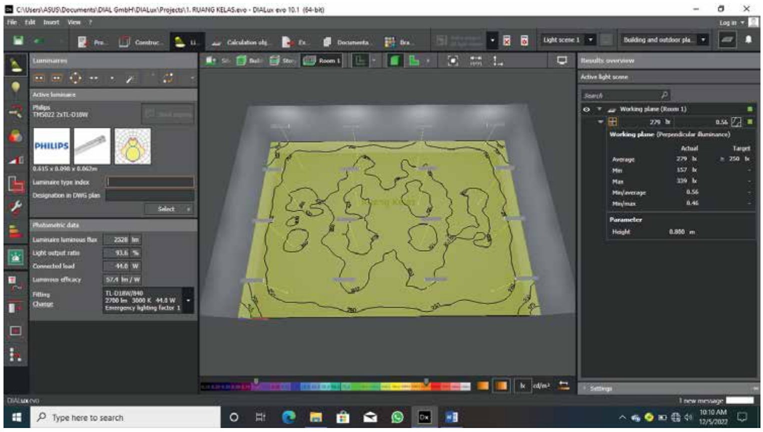

Figure 3.
Visual distribution of classroom light. Source: (DIAlux software).

4.2.2 Laboratory

There are nine laboratories (angklung room, drawing room, dance room, photography room, videography room, vocal room, acoustic room, recording room, orchestra room) with the same shape and room area. The following is a visualization of the placement of the light points, the distance between the lights, and the appearance of the light distribution (**Figures 4** and **5**).

From the measurement results, it is stated that 20 light points are needed with a distance between lights horizontally of 1.8 m and vertically of 1.68 m, a light strength (flux) of 31,222.8 lumens, and an average of 413 lux per square meter with the SNI target or standard, namely 350 lux.

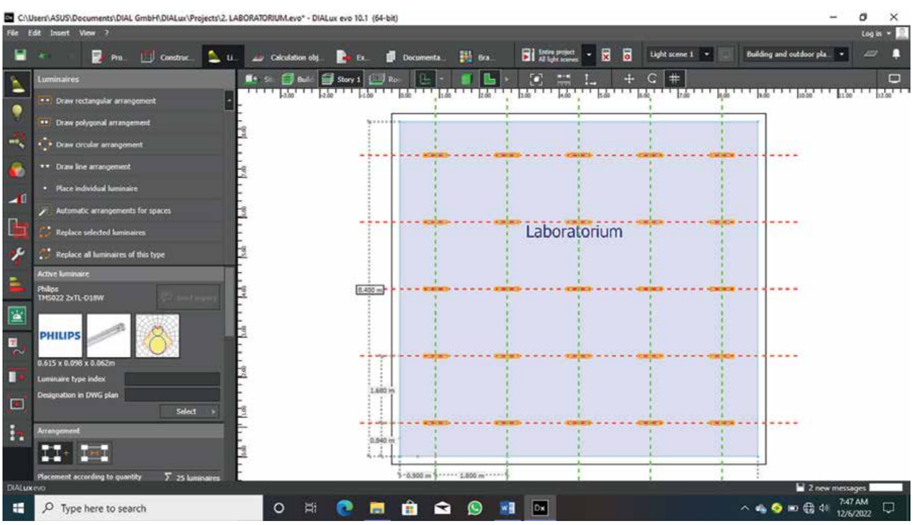

Figure 4.
Placement of laboratory light points. Source: (DIAlux software).

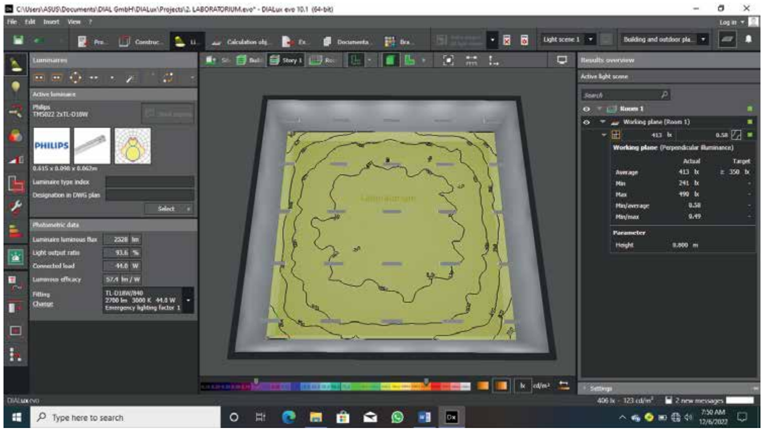

Figure 5.
Visual distribution of laboratory light. Source: (DIAlux software).

4.2.3 Public space

There are 15 public rooms (toilet, prayer room, archive room, lecturer room) with the same shape and room area. The following is a visualization of the placement of the light points, the distance between the lights, and the appearance of the light distribution (**Figures 6** and 7).

From the measurement results, it was stated that six light points were needed with a horizontal distance between lights of 1.833 m and a vertical distance of 1.725 m, a light intensity (flux) of 5464.8 lumens, and an average of 288 lux per square meter with the SNI target or standard of 250 lux.

4.2.4 Corridor

There are corridors on each floor of the FPSD building that are the same size. The following is a visualization of the placement of the light points, the distance between the lights, and the appearance of the light distribution (**Figures 8** and **9**).

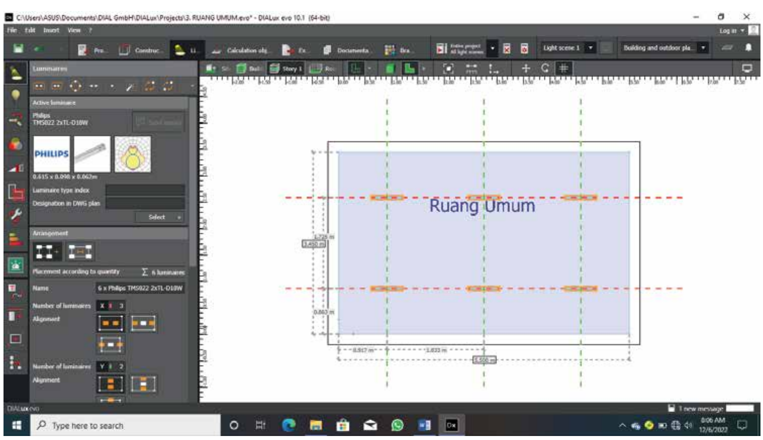

Figure 6.
Placement of public space light points. Source: (DIAlux software).

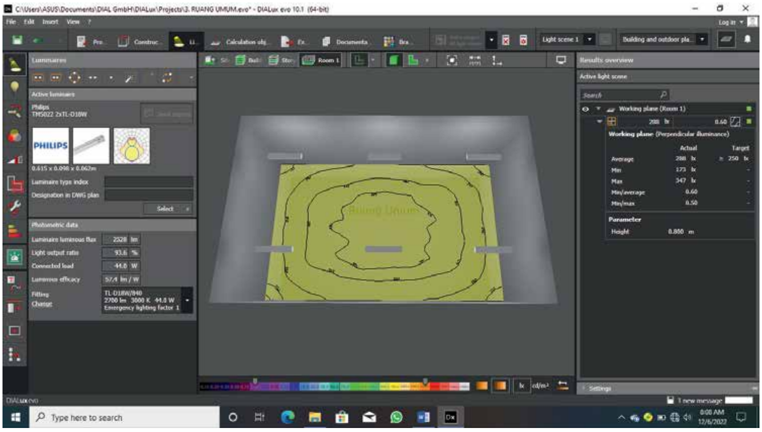

Figure 7.
Visual distribution of light in public spaces. Source: (DIAlux software).

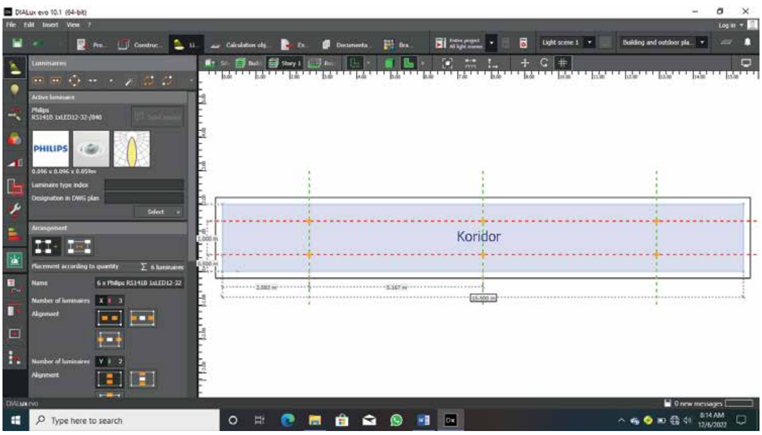

Figure 8.
Placement of corridor light points. Source: (DIAlux software).

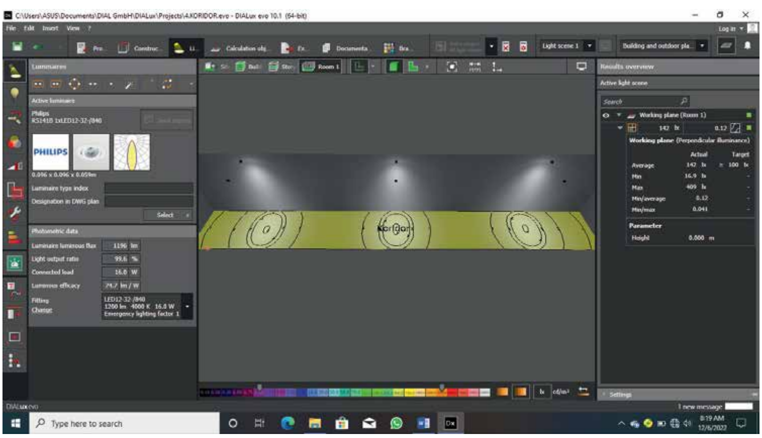

Figure 9.
Visual distribution of corridor light. Source: (DIAlux software).

Classroom wide 71 m^2					
Number of planning lights	**Number of DIALux lamps**	**F-total (Lumen) planning**	**F-total (Lumen) DIALux**	**E-average planning (Lux)**	**E-average DIALux (Lux)**
12	16	26.880	19.809	377,37	279
Standard SNI 250 Lux				Fulfill	Fulfill
Source: (Field and DIAlux software data).					

Table 3.
Classroom comparison results.

From the measurement results, it was stated that six light points were needed with a distance between the lights horizontally of 5.167 m and vertically of 1 m, a light strength (flux) of 4402 lumens, and an average per square meter of 142 lux with the target or SNI standard of 100 lux.

4.3 Comparison results

The following are the results of a comparison between the company's FPSD building lighting installation planning and the DIALux software design results (**Table 3**).

From the comparison results obtained, the planning requires the installation of 12 lamps with an average E of 377.37 and a total lumen of 26,880, while the DIALux design requires 16 lamps with an average E of 279 and a total lumen of 19,809. Both in planning and designing DIALux, DIALux has met standards (**Table 4**).

From the comparison results obtained, the planning requires the installation of 12 lamps with an average E of 353.27 and a total lumen of 26,880, whereas the DIALux design requires 20 lamps with an average E of 413 and a total lumen of 31,222.8. Both in planning and designing DIALux, DIALux has met standards (**Table 5**).

Laboratory wide 75.6 m^2					
Number of planning lights	**Number of DIALux lamps**	**F-total (Lumen) planning**	**F-total (Lumen) DIALux**	**E-average planning (Lux)**	**E-average DIALux (Lux)**
12	20	26.880	31.222,8	353,27	413
Standard SNI 250 Lux				Fulfill	Fulfill
Source: (Field and DIAlux software data).					

Table 4.
Laboratory comparison results.

Common room wide 18.9 m^2					
Number of planning lights	**Number of DIALux lamps**	**F-total (Lumen) planning**	**F-total (Lumen) DIALux**	**E-average planning (Lux)**	**E-average DIALux (Lux)**
2	6	4.480	5.464,8	231,17	288
Standard SNI 250 Lux				Unqualified	Fulfill
Source: (Field and DIAlux software data).					

Table 5.
General space comparison results.

Corridor wide 31 m^2					
Number of planning lights	**Number of DIALux lamps**	**F-total (Lumen) planning**	**F-total (Lumen) DIALux**	**E-average planning (Lux)**	**E-average DIALux (Lux)**
8	6	639,86	4.402	127,97	142
Standard SNI 250 Lux				Unqualified	Fulfill
Source: (Field and DIAlux software data).					

Table 6.
Corridor comparison results.

From the comparison results obtained, the planning requires the installation of two lamps with an average E of 231.17 and a total lumen of 4480, whereas the DIALux design requires six lamps with an average E of 288 and a total lumen of 5464.8. So the planning does not meet the standards, while the DIALux design already meets the standards (**Table 6**).

From the comparison results obtained, the planning requires the installation of eight lamps with an average E of 127.97 and a total lumen of 639.86, whereas the DIALux design requires six lamps with an average E of 142 and a total lumen of 4402. Both in planning and designing DIALux, DIALux has met standards.

5. Conclusion

In the FPSD building lighting intensity planning data, it is known that classrooms are 377.37 lux, laboratories are 353.27 lux, and corridors are 127.97 lux. The results of the planned lighting intensity have met the minimum standard for lighting intensity. However, the public space is 231.17 lux, which does not meet the SNI minimum standard for public space lighting intensity, namely 250 lux. So it is necessary to add lumens or install additional light points in the space.

In this research, DIALux software was used as a visualization medium for room lighting in the FPSD UPI Building. The DIALux software displays the appearance of the light distribution based on the lamps used and the target lux determined according to SNI standards for an educational room with various functions and can determine the number of lamps that need to be installed according to the lighting needs of a particular room. In the DIALux design results, the classrooms were 279 lux, the laboratories were 413 lux, the public rooms were 288 lux, and the corridors were 142 lux. The design results meet the SNI standards for lighting intensity.

The results of the comparison between the planning and design of DIALux showed differences in results, including differences in the number of light points, lux, and lumens. According to the planning data, most of the rooms in the FPSD building meet SNI standards; only the public rooms do not meet the standards. Meanwhile, in designing DIALux, the lighting intensity for each room meets the SNI standards for minimum lighting intensity.

Acknowledgements

The authors acknowledges the use of Grammarly and Google Translate for the language polishing of the manuscript.

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Chapter 7

Sustainable Textile-Based Building Envelopes: Enhancing Water and Energy Efficiency through Fog Harvesting

Maria Giovanna Di Bitonto, Nathaly Michelle Rodriguez Torres, Bin Liu and Alessandra Zanelli

Abstract

The perspective of future sustainable urban environments focuses on buildings that not only achieve energy efficiency but also actively contribute to sustainable water use. This chapter addresses the pressing challenges of urban water systems amid increasing water scarcity, exploring how innovative passive solutions like fog harvesting can complement traditional water sources and improve the energy efficiency of buildings. It examines the operational mechanisms of fog harvesting, the required atmospheric conditions, and its application in both urban and rural contexts. Case studies and water collection data are analyzed to showcase its potential. Particular attention is given to integrating fog harvesting into building envelopes, such as double-skin facades, which can collect water while reducing energy consumption in buildings through shading. Lastly, the chapter discusses the limitations of fog harvesting technology, its impact on urban water consumption, and its potential role in shaping a sustainable built environment.

Keywords: sustainable building envelopes, fog harvesting, water use efficiency, passive systems, textile architecture

1. Introduction

Water is a fundamental resource essential to sustaining life and functioning societies and economies. However, the rapid convergence of population growth, urbanization, and climate change is exerting immense pressure on global freshwater supplies. The Organization for Economic Co-operation and Development (OECD) projects a 55% rise in global water demand by 2050, driven by increased needs in manufacturing, thermal electricity generation, and domestic use [1]. A further contributor to this rising demand is the built environment, which is estimated to account for around 15% of global freshwater consumption, particularly through water-intensive activities such as material production, construction, and buildings' lifecycle [2]. These practices not only deplete natural resources but also lead to contamination and waste, creating severe risks to ecosystems and local water availability [3]. As urban areas continue to expand and the impacts of climate change intensify, the strain on water resources is expected to grow, raising serious concerns about future water security. This situation underscores the urgent need for innovative technologies and comprehensive studies to mitigate the looming threats to global freshwater supplies.

Water availability varies significantly between different climates, further complicating urban water management. In arid and semi-arid regions, such as Sub-Saharan Africa or the Middle East, water scarcity is exacerbated by naturally low precipitation levels and high evaporation rates [4]. For instance, countries in North Africa have access to less than 1000 m^3 of renewable freshwater resources per person annually, placing them in a state of chronic water scarcity [5]. In contrast, tropical regions, like Southeast Asia or parts of South America, experience abundant rainfall but are still vulnerable to seasonal shortages due to uneven distribution and challenges in water storage infrastructure [6].

Cities, now at the forefront of global urbanization, stand as the focal point for both the challenges and opportunities in addressing climate change. Urban areas are responsible for 71 to 76% of global energy-related GHGs [7], 40 percent of global resource use, and 40% of global waste streams [3], making them significant contributors to the climate crisis. With more than half of the world's population currently living in cities, the urban population is expected to increase to 6.3 billion by 2050 [8]. The rapid expansion of urban land, projected to grow by 1.2 million square kilometers by 2030, along with the rise of 10 additional megacities, each housing over 10 million inhabitants [9], heralds the expected massive scale of urbanization and the resulting increase in the size of the built environment. This surge in urbanization will intensify the pressure on natural resources, particularly water, at a time when global water demand is projected to rise by 40% by 2030 [10], resulting in a significant shortfall in freshwater supply.

Despite water's abundance—covering approximately 69% of the Earth's surface—less than 1% is suitable and accessible for human use [11]. Most of the Earth's water is found in oceans, which are not directly usable for drinking, agriculture, or most industrial processes without significant treatment. The small percentage of freshwater available is further concentrated in glaciers, ice caps, and underground aquifers, leaving an even smaller portion readily accessible in rivers, lakes, and reservoirs [12]. This scarcity underscores the fragility of freshwater resources, particularly in regions where demand is rapidly increasing.

Climate change further exacerbates this crisis by disrupting hydrological cycles. Shifts in precipitation patterns, higher evaporation rates, and more frequent droughts reduce water availability and introduce unpredictability in water supplies [13]. To address these interconnected challenges, innovative solutions are essential for sustainable water management, particularly in urban areas where the consequences are most severe. This underscores the critical need for novel systems that not only reduce water consumption in the built environment but also tap into alternative water sources, such as atmospheric water.

1.1 Challenges of traditional water resources in urban areas

Traditional water sources, including rivers, lakes, reservoirs, and groundwater aquifers, have been the cornerstone of urban water supply systems for centuries. These sources historically met the needs of urban populations, providing water for essential activities such as drinking, sanitation, and building amenities [14]. The development and growth of cities were made possible by their proximity to these water bodies, allowing for the construction of infrastructure like aqueducts, reservoirs, and treatment systems to distribute water efficiently [15]. However, the increasing pressures of rapid urbanization, population growth, and climate change have highlighted significant limitations in relying solely on these traditional water sources [16, 17].

One of the most pressing issues is the over-extraction of water, which has led to severe depletion of freshwater supplies. Groundwater aquifers, a critical source of water for many urban areas, are being pumped at unsustainable rates, often exceeding natural recharge capacities [18]. This has resulted in lowered water tables, land subsidence, and the intrusion of saltwater into coastal aquifers, further reducing the availability of potable water [19, 20]. Similarly, rivers and lakes, once considered inexhaustible, are facing reduced flow and contamination from industrial discharges, agricultural runoff, and untreated wastewater [21].

Compounding these issues is the growing demand for water in urban buildings and infrastructure. Modern cities require vast quantities of water for construction, cooling systems, landscaping, and amenities [22, 23]. As populations continue to rise and urban footprints expand, the strain on traditional water supplies is expected to intensify, exacerbating water scarcity. Furthermore, conventional water extraction methods often carry significant environmental consequences. Groundwater depletion disrupts ecosystems, while large-scale water transfers and desalination efforts have high energy demands and generate ecological impacts, such as brine discharge into marine environments [20, 24, 25].

In light of these limitations, there is an urgent need to explore non-traditional water sources as a means of achieving sustainable urban water supply. Alternative strategies, such as atmospheric water harvesting, rainwater collection, fog-water harvesting, and greywater recycling, offer viable solutions to reduce dependency on overstretched traditional systems [26–28].

1.2 Harnessing non-traditional water resources: A building-scale solution

As the limitations of traditional freshwater sources become increasingly evident, non-traditional water resources offer innovative solutions to address water scarcity. These methods not only supplement conventional water supplies but also promote sustainable water management practices within the built environment.

Atmospheric water harvesting captures moisture from the air, offering a renewable and decentralized water source. This technology is particularly valuable in arid and semi-arid regions where traditional surface and groundwater resources are limited [29, 30]. Rainwater collection systems are generally cost-effective, especially compared to other water supply methods, such as desalination or extensive infrastructure for groundwater extraction. However, their effectiveness does depend on seasonal rainfall patterns, which can vary significantly depending on the climate and region. This is why these systems require significant storage capacity [31] to ensure a reliable water supply during dry periods or when rainfall is insufficient. Despite these challenges, rainwater harvesting offers substantial benefits, including reducing reliance on centralized water networks, promoting water conservation, and providing an adaptable solution for both rural and urban contexts [32]. Urban buildings equipped with rainwater harvesting systems can significantly lower water consumption for activities such as irrigation, toilet flushing, and cooling systems [33].

Fog-water harvesting, a specialized form of atmospheric water capture, uses mesh or textile-based systems to collect water from fog. This method is especially effective in fog-prone coastal or mountainous regions [34]. Like rainwater harvesting, fog harvesting relies on environmental factors such as the frequency, intensity, and consistency of fog events.

These methods not only relieve pressure on natural freshwater sources but also offer opportunities for integration into sustainable urban design. For instance, architectural innovations such as textile-based building envelopes can be developed to collect and channel rainwater or fog water, addressing water scarcity while enhancing the energy efficiency of buildings. By capturing water before it reaches the ground, these systems reduce stormwater runoff, easing pressure on urban sewerage systems during heavy rainfall and mitigating urban flooding and combined sewer overflows [35], which are common issues in cities with aging drainage infrastructure. Additionally, incorporating water harvesting systems into the building envelope can improve energy efficiency by supporting passive cooling, reducing mechanical irrigation needs, and regulating building temperatures, thus lowering the demand for air conditioning and heating [36, 37]. When integrated into green infrastructure like green roofs and vertical gardens, these water harvesting systems create multi-functional solutions that contribute to urban cooling, biodiversity, and improved air quality [38, 39]. Captured fog or rainwater can be used for urban green infrastructure irrigation, reducing the need for potable water and promoting vegetation growth, further mitigating urban heat island effects [40].

These systems highlight the potential of non-traditional water resources to enhance water resilience in urban areas while supporting global goals for environmental sustainability and responsible urban development.

2. Fog harvesting technology

2.1 Fog harvesting

Fog harvesting is a technique for collecting water from fog, mimicking natural systems. Fog water is collected through passive devices called fog collectors, which are made of textile structures. These collectors must be oriented toward the prevailing wind direction to maximize water collection, as wind is a critical factor in the process. Once they reach sufficient weight, they flow to a gutter and are stored in tanks [41]. Over the last century, many fog collector designs have emerged, all featuring lightweight structures made of steel or wooden poles, capturing mesh, tension cables, gutters, and storage tanks.

2.2 Atmospheric conditions and suitable locations

Fog is a meteorological phenomenon composed of water droplets suspended in the air, forming a dense cloud layer in sustained contact with the Earth's surface [42]. Fog can be categorized based on its formation process, with the most common types being radiation fog, advection fog, and orographic fog [43]. The ones suitable to be harvested through fog collectors are advection fog and orographic fog. Advection fog forms due to horizontal air movement [44]. In advection fog, surface air cooling can occur when warm, moist air moves over cold surfaces. If the air is cooled to the dew point, fog is formed. Advection fog is also known as altitude fog, when wind-blown clouds form over mountains or hills, persisting as long as the wind presses the cloud against the terrain. Oro Orographic fog forms when air masses rise over steep terrain and then cool [45]. If sufficiently moist, fog will form on the surface. However, these processes often overlap, making it difficult to differentiate between them.

Many territories worldwide are affected by the fog phenomenon; many of them are in arid areas, while others are in territories that will face a hydric crisis in the upcoming years. Since ancient times, in arid fog oases, endemic flora and fauna adapted to those extreme conditions, developing certain characteristics to collect fog. Moreover, also indigenous populations adapted and conceived a vernacular collector. Most countries, in which a fog harvesting project has been developed, are situated in arid and semi-arid regions where potable water is scarce. According to Ref. [41], these nations encompass the driest areas of the western South American coast (Chile, Peru, Ecuador, and Colombia), the arid western coast of southern Africa (South Africa and Namibia), the Sub-Saharan region of East Africa (Eritrea and central Tanzania), the arid region of the Arabian Peninsula (Oman, Yemen, and Saudi Arabia), the dry region of the northwest African coast (Morocco), and the Mediterranean semi-arid region (Spain). Additionally, certain areas in southern Europe (e.g., Croatia) face water resource challenges due to hot, dry summers and mild, wet winters, combined with significant water demands for domestic, agricultural, and industrial purposes. A nearby cold-water current influences many of these regions, creating arid/semi-arid or Mediterranean climates conducive to increased fog collection at higher altitudes.

These countries have adopted fog collection technology because of their naturally favorable climatic and topographical conditions for potential fog formation. Most of these nations have high-altitude mountain ranges near their coastlines, typically more than 500 meters above sea level. Consequently, coastal climate patterns predominantly affect these mountain ranges, often experiencing advection and/or orographic fog for much of the year. For instance, in Chile, the northern section of the western coast experiences daily fog coverage [46]. In Colombia, this period extends to 210 days [47], in Peru 210 days, in Spain 142 days [48], and in Eritrea 166 days per year. These prolonged occurrences of dense fog in mountainous regions have prompted these countries to explore fog as an alternative water source, utilizing fog collection technology to address their water scarcity issues.

Identifying suitable locations for fog harvesting projects poses a significant challenge, primarily due to the transient nature of fog, which necessitates its control on solid ground. While satellite imagery offers an overview of cloud cover in the region, it lacks the precision required to pinpoint where the fog intersects with the Earth's surface. To discern these critical locations, a more practical approach is essential, one that entails a comprehensive ecosystemic analysis.

However, recognizing these promising locations is just the first step. Assessing the potential for fog harvesting is an evolving process. Currently, this feasibility is being evaluated through field test campaigns. These campaigns utilize a specialized device called a Standard Fog Collector (SFC), which will be discussed further in subsequent sections. The SFC plays a pivotal role in substantiating the effectiveness of fog collection within a given area.

To offer a practical perspective, **Figure 1** provides a map illustrating several locations where fog harvesting projects have achieved success. Nonetheless, it's important to emphasize that this map represents only a fraction of the extensive potential fog-harvesting sites. Numerous additional locations with untapped fog-water collection opportunities remain to be explored and assessed.

Currently, most fog harvesting projects are implemented in rural areas. However, there is significant potential for fog harvesting in urban environments, particularly in

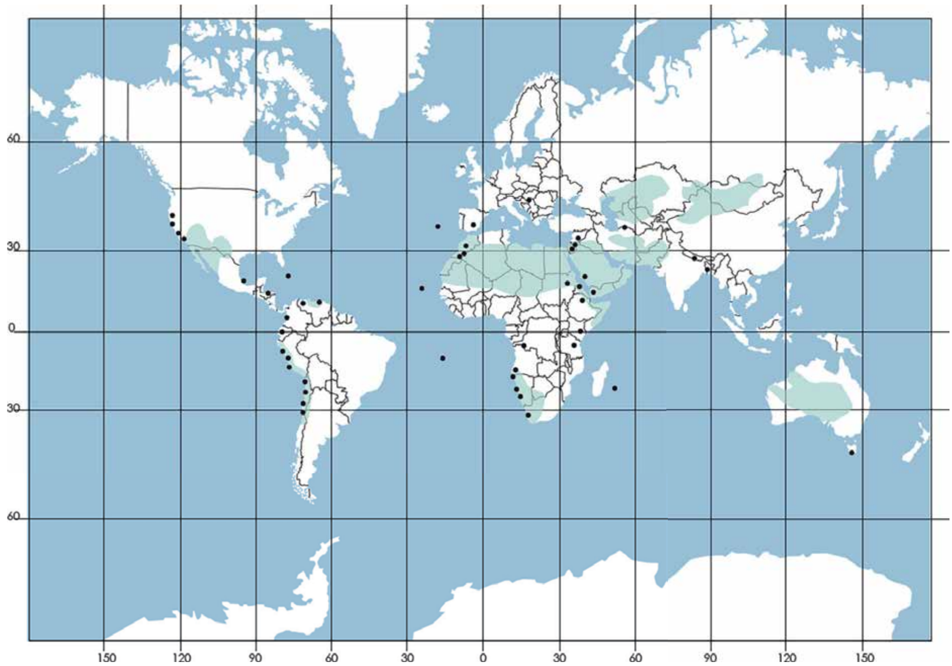

Figure 1.
Map of fog harvesting projects (Source: Elaborated by the author based on [41]).

cities situated in arid coastal regions where fog formation is well-documented, such as parts of the Arabian Peninsula, South America, and various islands.

2.3 Structure and design of fog harvesting devices

Over the years, as evidenced by historical research, various types of fog catchers have been experimented with the aim of maximizing fog-water capture. Nowadays, the most widely used capture system was designed by Fog Quest in 1980. It is the Large Fog Collector (LFC) the most economical, efficient, and easy-to-build fog catcher available. Several designs have been developed, and they differ in materials, implied shape-structure, and mesh components.

There are two types of fog catchers: those with a rigid frame structure and tensioned structures. In fog catchers with rigid frame supports, the "capture" surface is stretched continuously to the structure, while in tensioned structures, only the vertical poles are rigid elements, with all other elements being cables and tensioned mesh.

Most fog catchers installed worldwide feature two-dimensional structures consisting of a capture surface (Raschel mesh or similar) tensioned between two poles, perpendicular to the wind direction. These models vary in size and material, with different ground anchoring solutions. These solutions are simple and cost-effective but have issues, as previously mentioned, with mesh breakage or structural stability in strong winds.

Three-dimensional fog catchers are less common and are primarily associated with research experiments seeking to optimize water collection performance and, in some cases, structural stability against strong winds. Their three-dimensional shape makes them more suitable for situations where there are no predominant winds, and fog has multidirectional patterns.

The Standard Fog Collector (SFC) is the device usually used in fog harvesting research campaigns. It is a bi-dimensional structure, composed by a square frame that measures 1 m x 1 m, supported by two poles of 2 m high and two tensors. A height of 2 m is useful to intersect a strong wind speed, which is the greater the distance from the ground, and the tensors are useful to resist wind loads. The collection medium is a mesh, in particular the Raschel mesh, which is a 35% shade coefficient polypropylene mesh, utilized in a double layer [49].

The Large Fog Collector (LFC) is a 4 × 10 m flat screen, featuring a dual layer of Raschel mesh. Each mesh layer has a 35% shade coefficient and is composed of 1 mm flat filaments. The LFC's mesh is secured to two 2-meter-high anchored pillars, reinforced with cables fitted with tensioners, which can be adjusted depending on climatic conditions. Due to these cables, the LFC occupies considerable floor space, making it suitable for installation in areas with ample free space. However, when multiple LFCs are installed, they can share a center pole to optimize space usage. The cost of an LFC ranges from $1000 to $1500 [50], and its average annual yield varies from 3 to 12 liters per square meter per day, depending on location and season [51].

2.4 Case studies and collection data

The following Figure reports the general fog-water collection expressed in L/m^2 of mesh for several testing locations (**Figure 2**) [51]. Several research-oriented projects have been carried out in different countries to investigate the potential of fog-water collection using SFC devices. These assessments suggest a feasible daily fog collection rate of 30 L/m^2 in Oman [52, 53], 7.1 L/m^2 in Morocco [54], 6.2 L/m^2 in Saudi Arabia [53–55], 5.5 L/m^2 in Haiti [51], 4.5 L/m^2 in Yemen [56], 3.3 L/m^2 in Croatia [57], 2.51 L L/m^2 in the Dominican Republic [58], and 1 L/m^2 in Namibia [59].

Currently, the LFC is the most widely used fog collection technology globally. Analysis of various fog collection systems highlights their immense potential as a versatile solution for water scarcity. These systems have proven effective in arid and

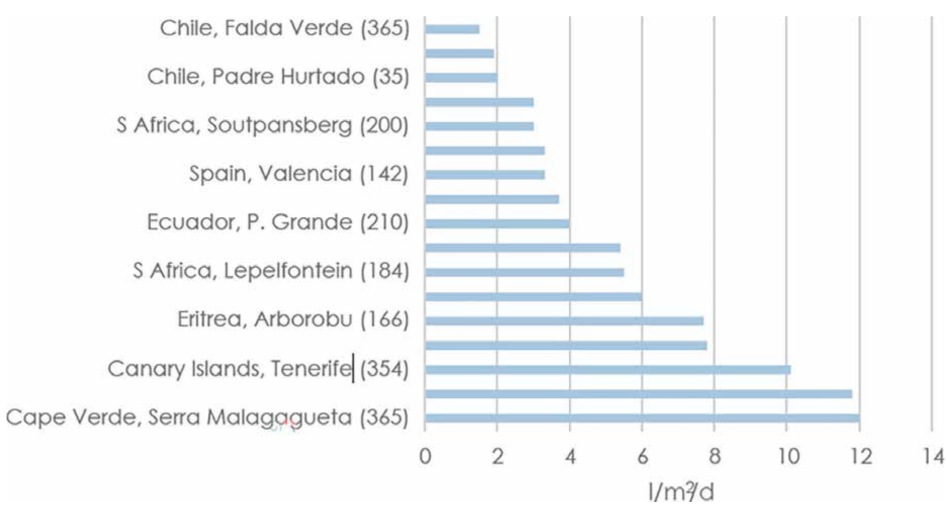

Figure 2.
Rate of fog collected (L/m²/day) for the countries that utilized the technology of fog collection. The average number of fog days per year is indicated in brackets (Source: personal elaboration based on [51]).

semi-arid regions, supporting agriculture, reforestation, and community water supply. Their sustainable nature aligns with the growing demand for alternative water sources.

The adaptability of fog collection technology allows for diverse applications, ranging from standalone structures for agricultural use to integrated solutions within urban infrastructure. This flexibility makes fog collectors an innovative and sustainable option for cities and rural communities alike.

3. Innovative approaches to fog harvesting for sustainable building envelopes

3.1 Integrating fog harvesting technology into buildings

3.1.1 Fog in urban areas and fog-prone cities

Urban areas worldwide face growing challenges related to water scarcity, rising energy demands, and sustainability [60]. The integration of fog harvesting technology into urban building envelopes offers a multifaceted solution to these critical issues [61]. Currently, there is a lack of international definitions of "fog-prone cities"; therefore, we will define cities with more than 30 fog events per year as fog-prone cities. This threshold is based on current advances in fog-water collection technology, which require recurring and consistent fog events for cost-effective operation. Consequently, when fog occurs for more than 30 days annually, implementing fog harvesting systems becomes both feasible and advantageous as a supplementary water source. These regions present optimal conditions for fog harvesting systems to capture atmospheric moisture. Notable examples include cities like San Francisco, USA, often referred to as "Fog City" due to its approximately 100 foggy days per year [62]; Chongqing, China, which experiences dense fog, particularly in spring and autumn, with over 100 foggy days annually [63]; and Cape Town, South Africa, where coastal fog is prevalent, creating significant potential for water collection [64]. These cities represent untapped opportunities for utilizing fog as a renewable water source, supported by advanced fog harvesting technologies.

3.1.2 Efficiency, water supply potential, and urban sustainability

Technological advancements have dramatically enhanced the efficiency of fog harvesting systems. Current systems can collect 10–20 liters of water per square meter per hour under optimal conditions, and recent breakthroughs have increased this capacity to as much as 70 liters per square meter per hour [65, 66]. Assuming an average fog duration of four hours, one square meter of fog collection net can harvest 40 liters per day or 1200 liters annually in cities with 30 foggy days per year. A 20-square-meter fog harvesting surface could provide up to 24,000 liters annually, sufficient to supplement 11% of the water needs for a four-person household consuming 600 liters daily. This underscores the potential of combining fog harvesting with building envelopes to achieve decentralized water solutions.

Daily per capita water consumption varies significantly across countries, as shown in **Table 1**. Assuming an average daily water use of 150 liters per capita, a fog harvesting surface covering 20 square meters can contribute a meaningful supplement to urban water systems, reducing dependency on traditional water sources. However,

Country	Approx. range (L/capita/day)	Primary source
United States	250–400	U.S. Geological Survey (USGS)
United Kingdom	140–150	UK Water Industry Research (UKWIR)
China	90–200	Ministry of Water Resources (China)
Spain	130–160	Spanish Ministry for the Ecological Transition
United Arab Emirates	300–550	UAE Federal Competitiveness and Statistics Centre
India	70–150	Central Public Health & Environmental Engineering Organization (CPHEEO)
South Africa	90–250	Department of Water and Sanitation (DWS); Stats SA; World Bank
Australia	150–250	Bureau of Meteorology (BOM)
General Sub-Saharan Africa (Rural)	30–90	WHO/UNICEF Joint Monitoring Programme (JMP)
Egypt	100–200	Holding Company for Water and Wastewater (HCWW)
Chile	120–200	Super Intendencia de Servicios Sanitarios (SISS)
Italy	150–200	Italian National Institute of Statistics (ISTAT)

Table 1.
Daily per capita water consumption in municipalities by country.

it is important to note that fog collection rates vary significantly depending on local climatic and geographic conditions. Factors such as fog density, duration, wind patterns, and elevation play a crucial role in determining water yield. Despite this variability, integrating fog harvesting technology remains a viable strategy to enhance the resilience of urban water supply systems, especially in fog-prone regions.

3.2 Opportunities and challenges of integrating fog harvesting with urban architecture

The integration of fog harvesting systems into building envelopes offers innovative architectural possibilities. Inspired by the Namib Desert beetle, advanced hydrophilic-hydrophobic surfaces enhance water collection efficiency while maintaining visual appeal [67]. These systems help reduce the urban water footprint by providing alternative water sources, thus alleviating pressure on traditional supplies and promoting sustainable water management strategies [68].

3.2.1 Opportunities

Fog harvesting systems provide a decentralized and sustainable water resource, alleviating stress on traditional water supplies. By capturing atmospheric moisture, fog harvesting reduces reliance on reservoirs, groundwater, and piped water networks. These systems can also be seamlessly integrated into urban infrastructure, such as rooftops and façades, to supply non-potable water for purposes like irrigation, cleaning, and cooling, enhancing overall water efficiency within urban systems [69]. Architecturally, fog harvesting systems complement modern building designs by serving as multifunctional elements. For example, integrating fog-harvesting meshes into dynamic façades provides both water collection and shading benefits, reducing interior heat gain and improving energy efficiency. Similarly, embedding these systems into green roofs and vertical gardens allows direct irrigation of vegetation, improving urban biodiversity, mitigating heat island effects, and promoting eco-friendly building practices [61]. Furthermore, fog-harvesting façades act as passive cooling devices, reducing solar heat gain and cooling energy demand by up to 20% [70, 71]. When combined with renewable technologies, such as solar panels, fog harvesting systems create hybrid components that optimize both water and energy resources, aligning with global sustainability goals like SDG 6 (Clean Water and Sanitation) and SDG 11 (Sustainable Cities and Communities) [72].

3.2.2 Challenges

Despite its potential, the performance of fog harvesting systems is constrained by environmental, architectural, and economic factors. Urban air quality, particularly in polluted areas, can clog fog-harvesting meshes with particulate matter, reducing efficiency; however, self-cleaning and photocatalytic coatings are being developed to mitigate this issue [73]. Additionally, consistent fog presence is essential for optimal water collection, making cities with sporadic fog events less ideal unless supplemented with other technologies.

Moreover, the urban wind environment poses a significant challenge for fog harvesting systems. Unlike rural or coastal areas with more predictable wind patterns, urban environments are characterized by turbulent and variable wind flows caused by high-rise buildings, narrow streets, and irregular architectural features [74]. These factors can reduce the efficiency of fog-harvesting systems by disrupting the consistent airflow required for effective fog collection [61]. Moreover, urban areas with predominant vertical wind flows may require adaptive designs, such as three-dimensional fog collectors or systems capable of capturing fog from multiple directions, to maximize efficiency [75]. Computational fluid dynamics (CFD) modeling can help optimize system placement and design in complex urban wind conditions.

The urban heat island (UHI) effect also impacts the performance of fog harvesting systems. The elevated temperatures in urban areas compared to their rural surroundings can reduce fog density and duration, as warmer air holds more moisture, making it less likely to condense into droplets [76]. This phenomenon is particularly pronounced in cities with extensive paved surfaces and minimal vegetation. Strategies to mitigate UHI effects, such as increasing urban greenery and implementing reflective building materials, could indirectly enhance fog-harvesting potential by maintaining cooler microclimates conducive to fog formation.

Integrating fog harvesting systems into diverse architectural designs also presents challenges. For example, the visual impact of mesh structures may conflict with the esthetics of heritage or modern buildings, prompting the development of innovative designs like transparent or patterned meshes. Space constraints in densely populated urban areas further limit opportunities for large-scale water collection, although vertical integration in high-rise buildings offers a viable solution. Maintenance and durability are significant concerns, as accumulated dust, pollutants, and debris on fog-harvesting meshes require regular cleaning to maintain efficiency. Advanced self-cleaning coatings and hydrophobic materials address this issue, but material degradation caused by UV radiation, acid rain, and industrial pollutants necessitates the use of durable, UV-resistant, and corrosion-resistant materials [77]. Economic barriers, including high installation costs and uncertain cost-effectiveness, pose additional challenges. Advanced fog-harvesting technologies, particularly those integrated into building façades, require significant upfront investments, which may deter adoption in regions with low fog frequency or abundant water resources. Conducting site-specific cost-benefit analyses is essential to ensure economic feasibility and justify the widespread implementation of this promising technology [78].

3.3 Advanced technologies for enhancing fog harvesting in building envelopes

Recent advancements in fog harvesting technology have significantly enhanced its potential for integration into building envelopes. These developments hold promise for addressing key challenges such as mesh clogging, the need for consistent fog conditions, esthetic integration, maintenance durability, and cost-effectiveness, as highlighted in Section 3.2. This section explores cutting-edge advancements in materials, coatings, and structural designs, showcasing how these innovations enable the application of fog harvesting technology on building surfaces.

3.3.1 Mesh designs and aerodynamic optimizations

Advanced mesh designs and aerodynamic optimizations are addressing the unique challenges of fog collection in urban environments, where turbulent wind patterns and space constraints are common. Macro-scale aerodynamic features, such as curved or cylindrical configurations, guide airflow effectively over collection surfaces, enhancing droplet capture in areas with erratic wind conditions [79, 80]. Meanwhile, micro-scale designs like perforated grids and harp-shaped structures stabilize localized airflow, ensuring consistent droplet deposition and reducing water loss [81, 82]. Layered mesh systems with varying pore sizes and nanoengineered hydrophilic-hydrophobic coatings create a cascading capture effect, reducing droplet loss from evaporation or erratic winds [83]. Modular and cost-effective multilayer textiles, capable of boosting water collection efficiency by up to 40% compared to single-layer designs, are increasingly integrated into urban structures such as façades, rooftops, and shading devices [84].

To further enhance efficiency, IoT-enabled adaptive mesh systems adjust their orientation based on real-time wind conditions, maximizing performance in variable urban environments [85, 86]. These innovations make fog collection systems more efficient and adaptable for dense urban landscapes, enabling their seamless integration into diverse architectural settings and expanding opportunities for decentralized water supplies in water-scarce cities.

3.3.2 Advanced materials and coatings

Recent advancements in material science have significantly improved fog harvesting systems for urban applications. Nanoengineered hydrophilic-hydrophobic coatings, inspired by natural collectors like the Namib Desert beetle, combine water-attracting and water-repelling zones to optimize droplet capture and prevent clogging [87]. These coatings enhance fog collection efficiency, allowing systems to achieve higher yields with smaller or fewer meshes, which reduces initial material costs for large-scale installations. Additionally, their self-cleaning properties minimize the accumulation of dust and debris, lowering maintenance frequency and operational expenses. Improvements in nanotechnology have made these coatings more cost-effective to produce, enabling the scalability of fog harvesting systems for widespread urban use.

A promising direction for future research is the direct application of hydrophilic-hydrophobic coatings to building surfaces, transforming passive areas into functional fog collectors while preserving architectural esthetics. However, challenges such as coating durability, technical integration with various building materials, and long-term structural impacts require further study. Meanwhile, advancements in mesh materials, including UV-resistant polymers and corrosion-inhibiting coatings, have improved durability and resilience to harsh urban conditions like pollution, acid rain, and prolonged UV exposure [88]. These innovations extend the lifespan of fog harvesting systems, reducing the need for frequent repairs or replacements, and further support the cost-effectiveness of this technology in urban environments.

3.3.3 Maintenance, durability, and esthetic integration

Ensuring long-term efficiency in urban conditions requires new maintenance strategies and durable materials. Self-cleaning coatings mimic the lotus leaf's water repellency, naturally removing dust and pollutants without frequent manual cleaning [89]. Strengthened alloys and corrosion-resistant composites provide greater resilience against UV radiation, industrial emissions, and acid rain, contributing to lower replacement costs over time [90]. When esthetic considerations are paramount, dynamic or transparent, fog-harvesting meshes can be seamlessly incorporated into façades; similarly, integration with green infrastructure (e.g., vertical gardens or green roofs) not only preserves visual appeal but also delivers dual benefits of water collection and sustainable building design.

3.4 Future applications and development potential

The future of fog harvesting technology lies in its potential to address water scarcity and energy challenges in urban environments. With continuous advancements in materials science, architectural integration, and hybrid technologies, fog harvesting systems are poised to play a transformative role in sustainable urban development. This section explores the future applications and development potential of fog harvesting technology, focusing on hybrid solutions, urban integration, and its contribution to resilience and sustainability.

3.4.1 Hybrid technologies: Multifunctional building envelopes

Integrating fog harvesting with other sustainable technologies can significantly expand its impact in urban settings. One emerging trend involves hybrid façades that simultaneously collect atmospheric moisture and harness solar energy, using the captured water to clean photovoltaic panels and improve their efficiency [91]. Embedding fog-harvesting meshes into vertical gardens or green roofs likewise creates self-sustaining systems, where plants benefit from a decentralized water source while contributing to biodiversity and mitigating the urban heat island effect [61]. Smart Internet of Things (IoT) sensors further enhance this concept by monitoring real-time environmental data—such as humidity, wind speed, and temperature—to optimize fog collection and minimize water waste. Linking these systems to city-wide frameworks can facilitate dynamic water redistribution and more responsive urban planning.

3.4.2 Urban integration: Retrofitting and new construction

Fog harvesting systems can be installed on existing buildings with minimal architectural modifications, thanks to lightweight and modular panel designs. Cities like Lima and Stuttgart have successfully retrofitted older structures for decentralized water collection, preserving both functionality and esthetics [92, 93]. In new constructions, fog-harvesting technologies can be integrated into double-skin façades, shading devices, or rooftops, seamlessly complementing sustainable building certifications such as LEED or BREEAM. Direct application of nanoengineered hydrophilic-hydrophobic coatings to surfaces like walls or glass façades can further reduce installation complexity and costs. This approach effectively maximizes harvesting area without altering building appearance—a crucial factor in dense urban environments.

3.4.3 Contribution to urban resilience and sustainability

By providing a decentralized, renewable source of fresh water, fog harvesting bolsters urban resilience against water scarcity and infrastructure vulnerabilities. Cities prone to drought—such as Cape Town—stand to benefit from supplementing municipal water supplies with fog-based collection. Because fog harvesting requires minimal energy, it aligns well with climate goals seeking to reduce overall carbon emissions. Beyond large-scale applications, small community installations in parks, schools, or neighborhood markets can facilitate equitable water distribution and help mitigate the impacts of climate change on local populations. As these networks scale, they can transform entire urban districts into more sustainable and adaptive environments, directly supporting global sustainability goals by improving water security and reducing the strain on centralized systems.

4. Conclusions

This chapter highlights the promising potential of integrating fog harvesting technology into sustainable building practices as a solution to urban water scarcity and energy efficiency challenges. The analysis underscores how fog harvesting systems, inspired by nature and advanced through modern material science, can effectively supplement traditional water sources in fog-prone regions. By incorporating these systems into building envelopes, such as double-skin façades or rooftop installations, buildings can reduce dependency on centralized water supplies while simultaneously improving energy performance through passive cooling and shading. Despite current limitations, such as dependency on specific atmospheric conditions and high initial costs, advancements in hydrophobic-hydrophilic materials, IoT-enabled systems, and aerodynamic designs pave the way for scalable, efficient, and esthetically integrated solutions.

Looking forward, the integration of fog harvesting into building technology offers transformative potential for addressing global sustainability goals. As urban constructions grapple with the twin pressures of rapid urbanization and climate change, adopting decentralized and renewable water resources like fog collection becomes not only viable but imperative. Future developments should focus on addressing existing challenges, including urban wind variability, mesh maintenance, and cost-effectiveness, through continued research and cross-disciplinary collaboration. By embedding fog harvesting within the fabric of building design, planners and architects can enhance urban and constructive resilience, reduce environmental footprints, and create a blueprint for sustainable cities equipped to thrive in the face of environmental uncertainty.

Conflict of interest

The authors declare no conflict of interest.

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Chapter 8

A Comparative Life Cycle Assessment of Façade Retrofit Strategies by Using Bio-Based Materials and UltraLightweight Building Systems

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Abstract

Energy retrofitting is central to Europe's goal of carbon neutrality by 2050. Building envelopes, responsible for 50–60% of total buildings' heat transfer, are critical for operational savings, while their retrofitting can additionally impact their embodied carbon. This chapter presents a Life Cycle Assessment (LCA) of three non-conventional retrofitting strategies based on the addition of lightweight technologies and low-carbon materials to an External Thermal Insulation Composite System (ETICS): 1. A commercially available lightweight polymeric textile cladding; 2. A fully biogenic mycelium composite insulating panel made with bio-residues, tested at the laboratory scale; 3. A bio-based insulating panel made of post-consumer textile waste. Each strategy is assessed individually, with the lightweight system also evaluated in combination with both bio-based and conventional insulating components. The assessment will consider the product stage (from cradle-to-gate) and end of life scenarios, in compliance with the EN15804 and/or ISO 14025.

Keywords: life cycle assessment, façade retrofitting strategies, lightweight systems, textile wastes, bio-residues, mycelium composite

1. Introduction

The building envelope has progressively gained momentum for retrofitting purposes. As a boundary subsystem, it influences and controls interactions between prevailing external conditions and regulated indoor comfort [1], and thus its improvements are one of the most effective retrofit interventions [2]. Retrofitting façades can significantly reduce energy consumption and associated CO_2 emissions, addressing up to 50% of a building's total energy use [3, 4] and up to 25% of the total in the residential sector [5].

Depending on the retrofitting goals, interventions may include adding thermal insulation or shading systems, replacing glazing with high-performance alternatives, or integrating active measures such as renewable energy systems.

Among common practices, adding insulation on a façade is functional to energy conservation, while shading components can promote energy modulation and mitigate overheating, particularly in glazed buildings, and improve esthetic qualities. Indeed, it is reported that increasing building envelope thermal resistance, thermal storage, and solar absorptivity reduce HVAC system energy consumption by 20–80% [6–8] depending on climatic conditions.

However, the embodied burdens associated with these additional materials are often overlooked, as recent studies indicate that the embodied impacts of new components can account for 10–80% of total lifecycle emissions [9].

Therefore, as buildings become more energy-efficient [10], the focus is shifting today from merely optimizing operational energy performance to making more responsible choices over the design stage concerning materials and adopted technologies [11, 12].

In this context, Life Cycle Assessment (LCA) becomes a crucial tool and shifts from a retrospective approach to a prospective one to guide design decisions rather than evaluating outcomes after implementation.

1.1 Objectives and methodology

This chapter conducts a prospective LCA for two main retrofitting scenarios adopting different principles of energy efficiency. These studies, conducted within the Textile Architecture Network (TAN) research group, propose first two diverse bio-based applications improving façade energy conservation; secondly, an application for energy modulation opting for the reduction of material use through the adoption of lightweight systems. More specifically, using an External Thermal Insulation Systems (ETICS) wall as a reference, the following paragraphs are going to analyze:

1. Bio-based insulating panels made either from post-industrial textile residues through thermobonding, or agricultural bio-residues through mycelium growth, aimed at improving the building's energy conservation and thermal performance of opaque façades;

2. Textile-based cladding solutions, compared to traditional shading systems, such as aluminum, address summer overheating challenges in glazed façades while reducing material usage, installation costs, and time.

A static attributional cradle-to-gate LCA (A1–A3) is going to be conducted by adhering to EN 15804:2012 + A2:2019. Indeed, phases A1–A3 are mandatory to produce Environmental Product Declarations (EPDs), as specified by the EN16783:2024.

All the studies thus include raw material production, energy supply, and foreground manufacturing processes, and related transports needed for 1 m^2 of a renovated ETICS wall system with a reference U-value of 0.28 W/Km located in Milan, which represents the main functional unit, to which the input and output data are normalized (**Figure 1**).

In this context, the functional unit of 1 m^2 varies in significance depending on the retrofitting strategy. Indeed, while in the analysis of the bio-based insulation panels the materials' processing—i.e., the type of adopted material—is a crucial factor, in the

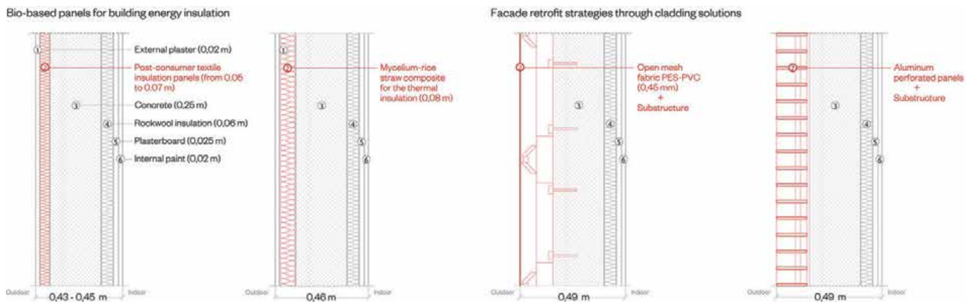

Figure 1.
ETICS wall and the different retrofitting technologies analyzed.

LCA of the textile-based cladding solutions the proportion between cladding materials and its substructure—thus the amount of material—is crucial.

The analyses are respectively conducted by using the LCA softwares SimaPro 9.6.0.1 and OneClickLCA with the databases EcoInvent 3.10 and GaBi, respectively.

After a brief theoretical overview of the LCA methodology, structured paragraphs are going to explain each study.

Lastly, the chapter identifies key innovations, limitations, and potential future research directions.

By doing so, this study highlights possible advantages and drawbacks of innovative retrofitting approaches to define their potentialities and to guide thus their responsible future industrial scaling for retrofitting applications.

2. LCA theory: Bio-based materials and lightweight systems

In the building sector, life cycle approaches, including LCA and Life Cycle Cost (LCC), provide a methodological framework for evaluating and comparing design choices, ranging from products to construction systems [13]. LCA, regulated by international (ISO 14040:2006, 14,044:2006) and European standards (EN 15978 and EN 15804), counts specific phases across the entire life cycle, including material consumption and manufacturing (A1–3), construction processes (A4–5), use stage (B1–7), end of life scenarios (C1–4), and eventual reuse of components (D), with each phase considered as a single unit process with input and output flows.

Considering the shift of impacts from operational energy to embodied energy in future energy-efficient buildings, LCA application is crucial to substantiate the environmental claims of adopting less impactful solutions—such as bio-based materials, waste-sourced materials, and lightweight systems—for building retrofitting purposes.

2.1 LCA of bio-based building components

When talking of LCA of bio-based building components, several unresolved methodological questions emerge.

The risk of burden-shifting across different life cycle phases and impact categories increases significantly [14]. Moreover, in the construction sector, the assumption that bio-based materials are carbon neutral is increasingly questioned [15], as carbon storage in bio-based material production varies on the material's growth rate. For instance, fast-growing plants like straw and hemp sequester carbon rapidly

(1–5 years), whereas wood accumulates over decades [16]. Consequently, the time dimension becomes a critical factor in the analysis, although it introduces complexity.

Existing LCA methods (0/0 model, −1/+1 method) still struggle to fully capture the long-term carbon storage in bio-based materials [17], and dynamic LCA, though promising, remains underused due to its complexity [18, 19]. The variety of existing LCA approaches to biogenic carbon accounting, including static and dynamic methods, underscores the need for standardization within the international LCA community to ensure reliable results, particularly as bio-based materials become more widely adopted in construction.

2.2 LCA of lightweight building systems

In contrast, LCA studies on lightweight building systems stress the importance of assessing not only materials production but also their durability, including the impact of material weight on substructure sizing [20] and replacement needs over a realistic lifespan [21]. Among structural membranes, ETFE films have been proved to be more environmentally efficient than glass due to their lightness, which enables to use them even at the component level over conventional façade and roofing systems [22].

Their careful assessment shall consider the inherent characteristics of the material, such as lightness, thinness, and flexibility—positively impacting the sizing of the supporting substructure—together with the impacts that may result from their production, as they are synthesized from fossil fuels. Only considering both aspects, indeed, the significant environmental advantages of lightweight systems over conventional building materials can be highlighted [23].

3. Façade retrofitting for energy conservation: Upcycling secondary streams of material to produce alternative building insulation

This paragraph presents the LCA of two bio-based thermal insulation components, differentiated by the type of materials coming from different residual flows—fostering circular economy strategies in construction—and the relative manufacturing processes employed.

One strategy focuses on recycling solutions to upgrade post-consumer waste, while the other explores the exploitation of active organisms to valorize secondary streams coming from the agro-industrial sector.

The analyses utilize the EN 15804 cut-off approach, which distinguishes between waste and recyclables, promoting material reuse by excluding upstream burdens for recyclables. Indeed, the choice of allocation method is particularly relevant as it shapes the environmental profile of waste-based building materials and drives their innovation potential.

Both analyses include transports for their envisioned application in Milan, considering a target U-value of the renovated ETICS wall of 0.28 W/m^2 [24]. For this reason, the Italian energy mix is considered to quantify the electricity needed for the operation of each production stage.

3.1 LCA of post-consumer textile insulation panels

The textile industry is one of the main contributors to the consumption of natural resources and energy, driven by the “buy and throw away” culture. Indeed, the short timeframe between the production of garments and their disposal, combined with the difficulties associated with textile recycling due to the use of mixtures of different fibers, leads to the production of large amounts of textile waste. This issue is further intensified by the impending obligation imposed by the European Union to implement the separate collection of textile waste by 2025, highlighting the need for more sustainable End of Life (EoL) scenarios [25].

In this context, the research project "maTE.ria. Methods and Actions for the Ecological Treatment of Post-Consumption Textiles and their Innovative Recycling in Architecture," developed at Politecnico di Milano in 2021, aims to transform post-consumption textile waste into new secondary raw materials to produce high-recycled-content construction products.

Therefore, this section focuses on the environmental analysis of the production of four thermal insulation mats, differing in both composition and density. These mats are composed of pure cotton and pure polyester, as they are materials that dominate the market and significantly contribute to its environmental impact [26], or a blend of mixed fibers. By doing so, the study provides essential data for comparative evaluations and fosters awareness of the environmental implications and eventual potentials of recycling processes for the development of new materials.

Indeed, while interest in textile recycling is on the rise and some textile waste-based insulating products are already on the market, the availability of EPD and LCA studies in this field remains limited.

3.1.1 Product description: System boundaries and functional units

The assessment considers one panel from each textile cluster as well as a fourth panel, also made from textile waste, with higher density, which still retains good insulating performance. This approach enables an examination of the influence of density on the environmental performance of the panels.

In all four panels, the composition consists of 4% of an antistatic liquid, made from a mix of glycerin, ethoxylated synthetic alcohol, phosphate, and potassium salt, while the remaining 96% is made up of a mixture of waste fibers of different natures, depending on the cluster of origin, and a bicomponent fiber in Polyethylene (PE)/Polypropylene (PP), later defined as "binder." Of this 96%, 90% is made up of the waste fibers and 10% of the binder. In the case of the higher density panel, the fiber-to-binder ratio changes to 80% and 20%, respectively.

The involved supply chain for the production of 1 m^2 of post-consumption textile insulating panel includes a plant capable of sorting about 300 garments per hour and a pilot line on an industrial scale capable of processing up to 600 kg/h of material. Each type of panel analyzed has a thermal conductivity value that varies depending on the density. For panels with lower density, the values range from 0.04 to 0.05 W/mK, while for the high-density panel, the conductivity reaches 0.05 W/mK. The thickness ranges from 0.05 to 0.07 cm, ensuring a thermal transmittance of the wall equal to 0.28 W/m^2K.

3.1.2 Process description and flowchart

The production process of post-consumption textile insulating panels consists of five main macro-phases: collection, sanitization, sorting, transport, and reprocessing (**Figure 2**).

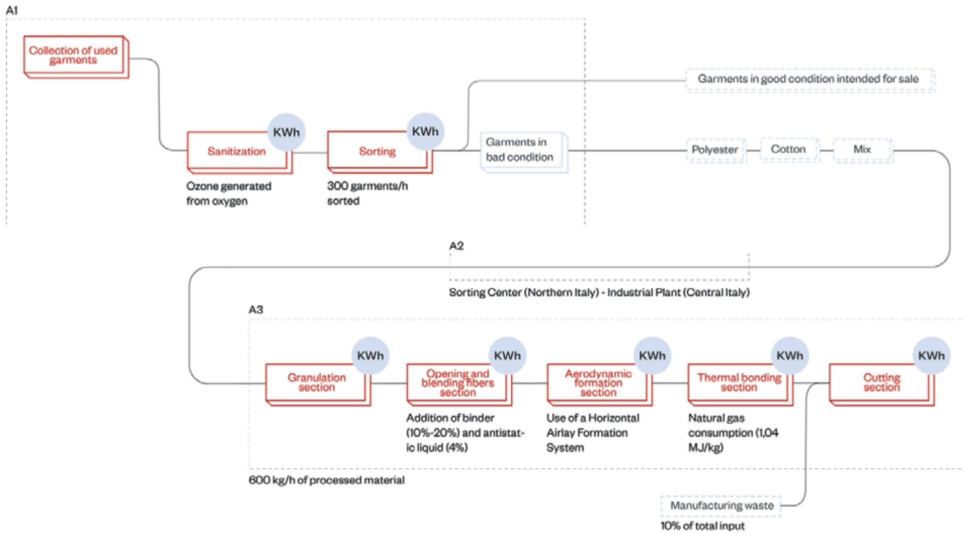

Figure 2.
Flowchart of Post-Consumer Textile Insulation Panels (A1–A3).

The collection phase involves the retrieval of used garments from designated bins distributed across the country, followed by transport to the sorting center, which is carried out by road using diesel-powered vehicles.

Upon arrival at the sorting plant, the garments are moved through a semi-automated system consisting of conveyor belts that direct the material to silos, through which the garments proceed to manual sorting stations. Along the way, the garments are sanitized using ozone generated from oxygen to ensure safe and healthy working conditions for the operators involved in the process.

At the manual sorting stations, skilled operators divide the material into the three selected clusters. Following this phase, the clusters are transported by road to the industrial site where the panels are produced. For this analysis, the industrial site was identified as the partner facility that developed the pilot line, located in central Italy.

At the industrial plant, the clusters undergo different stages. In the granulation section, the garments are shredded until they reach the size of flakes. In the opening and blending fibers section, the flakes are evenly mixed with the antistatic liquid and the binder in the aforementioned percentages, ensuring workability and cohesion, respectively. In the aerodynamic formation section, fibers are distributed horizontally in an even manner to form a mat. Then the mat undergoes a thermal treatment in the thermal bonding section to activate the binder and stabilize the structure. In the cutting section, the semi-finished panel is sized according to the requirements.

The production waste percentage generated during the process is approximately 10% of the total material input.

3.1.3 Data collection and assessment

Primary data have been collected from direct surveys and meetings with the partners to define the flows of substances entering and leaving each unit process, in terms of resource consumption and environmental emissions.

The consumption associated with the extraction and processing of resources includes fuel, energy, and oxygen, used for collection, sanitization, and the operation of the sorting plant. These consumptions were calculated based on the annual collection and sorting capacity of the plant, considering an operation of 240 working days per year, with 8 working hours per day and an average collection round of 105 km. The resulting values were then scaled according to the percentage of garments collected for each cluster, namely: 3% for the Pure Cotton cluster, 3% for the Pure Polyester cluster and 9% for the Mix cluster.

For the production phase, consumptions were calculated per kg of processed material. These values were then multiplied by the weight of the considered functional unit. Below are the consumption values per kg determined by the machinery used along the pilot line: (1) Electricity consumption: 55% of the total installed power, equal to 0.5 kWh; (2) Compressed air consumption: 0.007 m^3 at a pressure of 6 bar; (3) Methane gas consumption: 1.04 MJ.

For the transportation phase, the distances considered are referenced in the "Process description and flowchart" section.

3.1.4 Results

The obtained results are consistent with those reported in the literature and EPD of similar products, highlighting a substantially homogeneous behavior among the three types of lower density panels, despite their origin from different clusters. The higher density panels exhibit higher GWP values due to the higher percentage of binder, which emerges as a discriminating factor.

In detail, the lower density panels have a GWP of 0.097 kg CO_2 eq./kg (**Figure 3**), which, for the higher density panels, rises to 1.12 kg CO_2 eq./kg (**Figure 4**).

The production phase (A3) is the most impactful, primarily due to the substances involved in the process. In contrast, for the transport phase (A2), the impacts are of little significance compared to the entire production process.

3.1.5 Discussion and final consideration

As previously mentioned, the comparative assessment, shown in **Figure 5**, highlights how the panels developed in the research align with what is available on the market and in the literature in terms of GWP.

In terms of impact distribution, the A3 phase is the most impactful, even though the greatest impacts are not related to energy consumption but to the presence of the binder and of the antistatic liquid. Often, among the end of life scenarios, recycling,

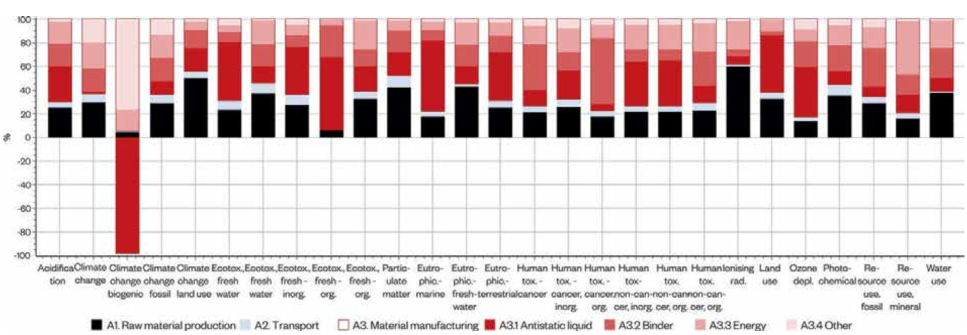

Figure 3.
Results of low-density panels (A1–A3).

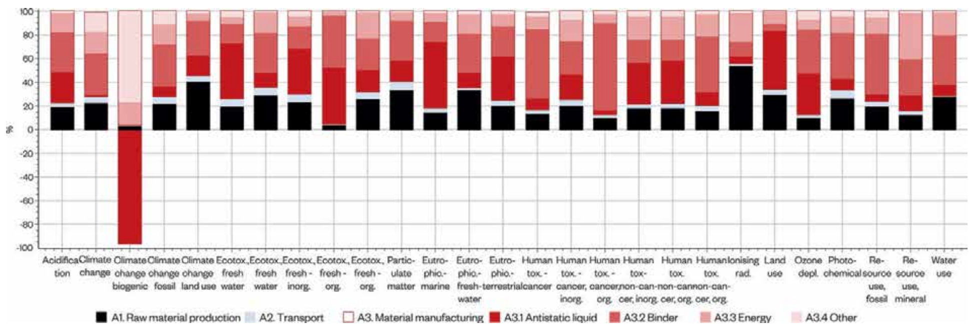

Figure 4.
Results of high-density panels (A1–A3).

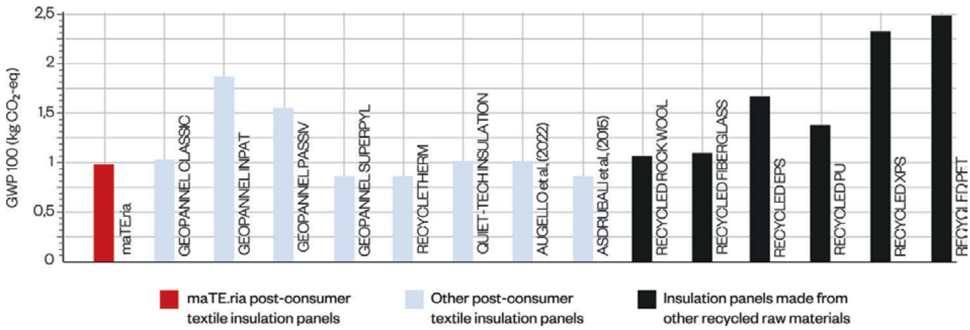

Figure 5.
GWP comparison of maTE.ria panels and other recycled insulation products.

while reducing emissions and the use of virgin raw materials, results in higher energy consumption compared to other EoL solutions, such as incineration with energy recovery. The energy no longer recovered through incineration still needs to be used to complete recycling processes, which are often highly energy-intensive [27]. However, the results of this analysis show how, along the developed supply chain, this risk is contained, highlighting the competitiveness and effectiveness of the consortium.

The A2 stage, regarding transport, has relatively low impacts compared to the entire production process. However, consumption could be further reduced by replacing the current diesel vehicles with less impactful models during the collection of second-hand garments.

Moreover, further analysis might imply the possibility of locating an industrial site where the panels are produced near the sorting center, minimizing negative externalities related to waste movement and emphasizing the importance of proximity in production supply chains.

3.2 LCA of mycelium-rice straw composite for the thermal insulation of façade systems

The current study has been developed in the framework of the MSCA European Project "ActaRebuild Training Network," within a research project investigating strategies for the net-zero energy retrofitting of curtain wall systems by using bio-based materials. In this context, the research explores the potential of mycelium composites to replace synthetic foams for thermal insulation of façade systems. Indeed, mycelium, the vegetative growth of filamentous fungi [28], has recently attracted significant attention for its potential contribution to climate change mitigation, including applications within the built environment. Mycelium acts as a natural binder by growing into lignocellulosic substrates to produce biodegradable composite materials. By doing so, it can upcycle waste into natural bio-foams, leveraging their porous yet rigid structure as a sustainable alternative to conventional non-biodegradable insulation materials such as expanded polystyrene (EPS) and extruded polystyrene (XPS) [29], which are still predominant in the market—representing respectively the 27.4% and the 36.3% of the global market for insulating components [30, 31]—although they have high environmental impacts.

Even though extensive research has highlighted the potential applications of mycelium composites in construction, such as insulation materials, acoustic panels, structural elements, and even packaging foams [32], studies regarding their environmental impact are still scarce. This paragraph thus contributes to widening the research by presenting the preliminary results of the LCA of a mycelium panel for thermal insulation as part of a larger investigation about mycelium composite applications from cradle to grave.

3.2.1 Product description: System boundaries and functional units

A small-batch pilot production at a laboratory scale consisting of a 15*15*4 cm sample of mycelium-rice straw composite with a conductivity of 0.06 W/mK is assessed and finally up-scaled to 1 m^2 for its application on a renovated ETICS wall with a thickness of 0.08 m, to reach the targeted wall performance of 0.28 W/m^2K.

Rice straw has been selected as a substrate among various agricultural by-products due to its abundant availability in the north of Italy, where the application of the mycelium composite as thermal insulation has been envisioned.

The species of mycelium utilized is Ganoderma Lucidum, as it grows faster, is more accessible and less susceptible to contamination during growth, and is one of the most documented and studied mycelium species in the world.

3.2.2 Process description and flowchart

The production process of the rice straw mycelium composite at a laboratory scale counts on 4 main phases: (1) Substrates sterilization; (2) Substrate inoculation; (3) Sample incubation; (4) Composite inactivation (**Figure 6**).

The sterilization process begins with manually shredding rice straw and mixing it with water at a ratio of 200% w/w inside autoclavable aerated bags. Filled bags are sterilized in an autoclave for 50 minutes at 120°C.

After cooling down, the sterilized substrate is inoculated under laminar flow to prevent potential contamination through the solid method of inoculation. 10% w/w of Ganoderma spawn on a rye-grain basis, supplied by a manufacturer from Belgium, is mixed to the initial sterilized substrate. Indeed, mycelium spawn is commonly made on a rye-grain basis and commercially available as such [33]. Bags filled with the inoculated substrate are then put into an incubator under a controlled environment with a constant temperature of 27°C and 60% HR.

After 1 week of incubation, 3D-printed molds made from PLA of 15*15*4 cm are disinfected with 70% ethanol, filled with the inoculated substrate, and repositioned

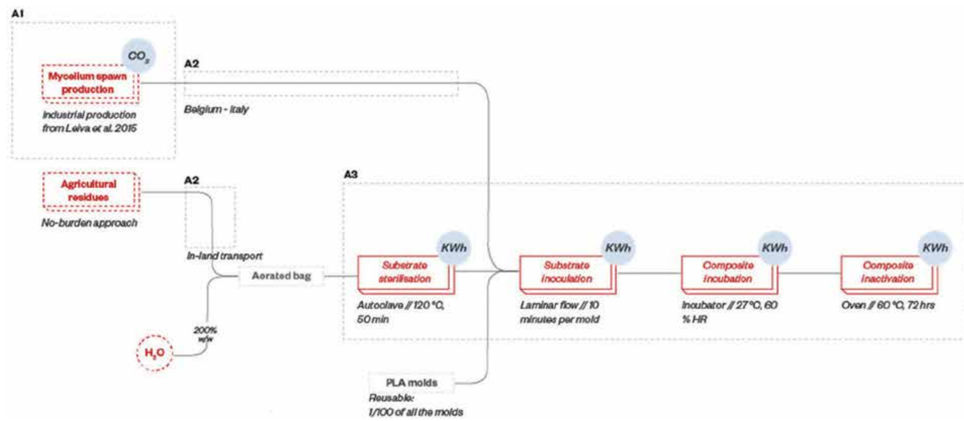

Figure 6.
Flowchart of mycelium composite production (A1–A3).

into the incubator for an additional week, for a total incubation period of 14 days. After demolding, mycelium composites are dried in an oven for 48 hours at a constant temperature of 60°C, while molds are cleaned and disinfected to be further reused.

3.2.3 Data collection and assessment

Primary and secondary data have been collected through the direct fabrication of the mycelium composite and literature sources. The analysis has been subdivided based on the subsequent fabrication processes. Quantities used for the production of 1 single sample of 15*15*4 cm have been scaled up to produce $1m^2$ of mycelium composite with a given thickness of 0.08 cm.

Mycelium spawn culture has been modeled as a subsystem of mycelium production based on literature data by Refs. [34, 35], as previously done by Weinland et al. [33]. Auxiliary materials, such as aerated bags and PLA molds, have been taken into consideration and modeled based on [35, 36]. PLA molds, which are potentially infinitely reusable, have been partially accounted for in the calculation, with 1/100 of the total quantity required for the production of 1 m^2 of mycelium composite included in the assessment. Disinfectant has been modeled as a solution made of 70% pure ethanol and 30% water. The environmental assessment of gloves has been omitted.

The electricity needed for the operation of each production stage has been modeled by multiplying the process duration measured in the laboratory (in hours) by the power requirements (in kW) as provided in the manufacturers' technical datasheets for the used equipment.

3.2.4 Results

The obtained results are consistent with other LCA studies on mycelium composites production (**Table 1**). More specifically, this rice straw mycelium 8 cm-thick insulating panel, with a density of 90 g/cm^3, features a GWP of 143.37 kg CO_2 eq./m^2, which corresponds to 1.69 kg CO_2 eq./kg.

In particular, the conducted analyses highlight the phase of process production (A3) being the most impactful (**Figure 7**), mainly due to the energy consumption of the inactivation process (**Figure 8**).

Source	Application	Density (kg/m^3)	Scopes	GWP (kg CO_2-eq)/kg	GWP (kg CO_2-eq)/m^2	GWP (kg CO_2-eq)/m^3
Enarevba & Haapala [37]	Packaging insert	111	A1–A3	0.9	—	101
Carcassi et al. [16]	Thermal insulation	229	A1–C4	0.55	46.13–83	127
Current analysis	Thermal insulation	90	A1–A3	1.59	11.47	143.37
Stelzer et al. [35]	Bricks	—	A1–A3	—	—	247
Livne et al. [36]	Bricks	163	A1–A3	1.64	—	267
Weinland et al. [33]	Acoustic insulation panels	178	A1–C4	1.57	—	280
Alaux et al. [38]	Myco brick	—	A1–A3	—	—	612

Table 1.
Comparison of the results of LCA studies on mycelium composites.

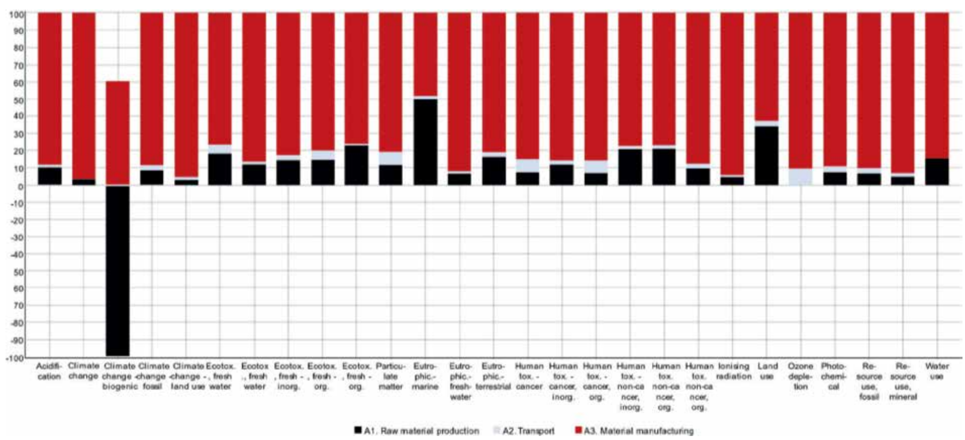

Figure 7.
Results of phases A1–A3 for 1m^2 of mycelium-straw composite.

Transports do not represent a huge burden, even though they consider the transfer of mycelium spawn from Belgium to Italy, where the production process is envisioned. Water consumption has a particular relevance during the sterilization process, as the composite made of rice straw requires 200% w/w due to its high rate of absorption. However, this value could be lower if other substrates with lower rates of absorption are used (such as, for instance, rice husks or sawdust).

3.2.5 Discussion and final consideration

This LCA study shows preliminary data for the application of a mycelium composite based on rice straw substrate for the thermal insulation of 1m^2 of ETICS façade.

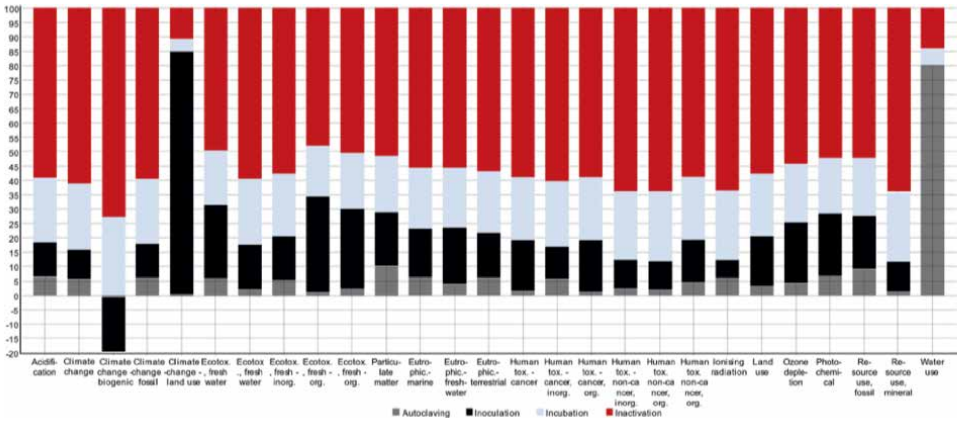

Figure 8.
Breakdown of the process stage.

As previously mentioned, results align with current collected and systemized literature and show a promising value of GWP per kg, which could be further reduced by increasing the composite density, which, however, might affect the composite thermal performance over time. Plastics have been partially considered, as suggested by previous LCA studies on mycelium composites [16, 39, 40]. However, the impact of this type of auxiliary material requires further investigation, as their impacts might be overlooked. Gloves, for instance, represent a disposable plastic source that deserves focused studies. In this regard, it is worth noticing that [38], considering the disposal of the gloves and plastic bags used in the lab, obtained a GWP value way higher compared to the other LCA (**Table 1**).

For what concerns the carbon potential of this composite, the study considers the embodied carbon of the rye substrates used for the production of mycelium spawn and applies the zero-burden methodology concerning rice residues coming from the agro-industrial sector. However, metabolic carbon is not taken into consideration. Indeed, mycelium, while growing, emits a certain amount of CO_2, which thus reduces its carbon storage capacity. Among LCA studies of mycelium composites, [36] only provides its assessment, reporting a reduction of the total carbon storage of the composite of 21%, which would correspond to the emitted carbon during the mycelium growth. This topic warrants further investigation, particularly regarding methodological approaches and potential influencing factors. Indeed, quantities of released CO_2 might depend on many different variables, such as fungal strain and substrate typology.

The production process could be further improved by its eventual scale-up. Indeed, laboratory scale production analyses involve way more energy and material consumption compared to industrial production. In this regard, studies report that scaling up mycelium composites production might lower its GWP up to 68% [35], which thus highlights the potential of these innovative biodegradable materials.

3.3 Final consideration

This chapter has introduced two innovative bio-composites for the thermal insulation of buildings, each based on distinct experimental manufacturing principles. One permits the re-introduction in the market of post-consumer textile wastes, which represent a huge environmental burden, while the other relies on the interaction of active organisms bonding vegetative substrates for the realization of a complete natural composite. Although produced at different scales—mycelium composites at laboratory scale and textile panels within the industry, using machinery adapted for that purpose—both technologies have shown promising results. Compared to more conventional materials, they both show lower GWP and land consumption values, as well as more favorable EoL scenarios. Specifically, mycelium composites are fully biodegradable, while textile mats can be potentially separated and reintroduced into the market, even though it has not been proven yet.

In this regard, it is suggested to explore the secondary application of such residues for their sustainable re-introduction in the same production chain, which asks for a critical understanding of the energy demands associated with reprocessing compared to the production of a novel insulation composite.

For mycelium composites, further research is needed to study their carbon potential. When mycelium grows on the substrates, it releases a certain amount of CO_2, which inevitably reduces its carbon storage capacity. Although, as previously mentioned, the literature on this topic is limited, the metabolic activity of mycelium remains a crucial factor in assessing the viability of these composites for widespread use in the construction sector.

Moreover, as both technologies are still experimental, their durability remains a key topic requiring more research. Applications in real-life case studies are essential for a comprehensive assessment of their long-term performance and feasibility.

4. Façade retrofitting for energy modulation: Lightweight solutions for building sun-shading

If the first part of the chapter compares two materials for building energy insulation, this section compares two façade retrofit strategies aimed at enhancing energy modulation and providing sun-shading. Among the current strategies for sun-shaded façade retrofit, perforated fabrics as fixed exterior shading devices allow for light penetration and reduce heat gain, improving energy efficiency [40]. Indeed, as climate change progresses and global temperatures rise, effective summer energy modulation is becoming critical even in those regions traditionally characterized by milder summers.

This study performs an LCA of two lightweight sun-shading solutions for retrofitting existing building façades to compare their environmental impacts and identify the relative contributions of the fixing tools and cladding layer.

The two solutions are characterized by comparable sun-shading performance and application methods—a metal substructure—but are respectively made of PES-PVC and perforated aluminum gratings. From an LCA perspective, while PES-PVC with its lightness and thinness permits to minimize the amount of needed substructure and still enables the coverage of larger façade spans, perforated aluminum gratings can be entirely composed of recycled materials, thereby reducing the environmental impact associated with raw material extraction and processing. To ensure consistent energy performance metrics across both solutions, the materials were considered with an airflow permeability of 14%.

4.1 Strategy description: System boundaries and functional units

As mentioned, this analysis focuses on the adopted mounting strategy rather than the applied product and its production process. Indeed, both studies compare the adopted substructure, the fixing components, and the final cladding material. Due to the varying properties and weights of the materials, the primary distinction between the two solutions is the quantity of substructure and fixing elements.

Considering that open mesh fabrics (PES-PVC) and aluminum perforated panels exhibit significant differences in their material composition and system dimensions, these factors were considered when scaling the analysis to the design of $1m^2$ of façade. This approach allows for accurate dimensioning of the fixing systems and facilitates the computation of the material flow chart in relation to the established functional unit.

For the transportation phase (A4), the default data given by each EPD for the city of Milan have been adopted. However, the transportation phase has a minimal effect on the overall impact.

4.2 LCA of textile cladding solution

4.2.1 Data collection and assessment

The PES-PVC pre-tensioned façade uses micro-perforated technical textiles made from PES-PVC open mesh. This innovative technology employs a substructure composed of aluminum profiles and steel fixing elements, onto which the pre-tensioned membrane is securely assembled. The quantities of the substructure have been calculated based on the research conducted by Ref. [21], specifically using data from the Adamello Case Study. These values were normalized to provide an accurate estimate per square meter ($1\ m^2$) of façade. It is important to note that while these quantities are parameterized for $1\ m^2$, they do not directly correspond to the actual requirements for constructing a $1\ m^2$ façade.

Table 2 presents the materials employed in the PES-PVC membrane analysis along with their characteristics in terms of LCA. Notably, both the aluminum profiles and steel fixing elements incorporate recycled material, contributing to a reduced environmental impact.

The PES-PVC open mesh weights $0.51\ kg/m^2$ with a thickness of 0.45 mm, the steel fixing elements add a total weight of $0.52\ kg/m^2$ (approximately 0.03 kg/unit), while the aluminum profiles used for the frame contribute $2.1\ kg/m^2$.

4.2.2 Results

The LCA analysis reveals that the PES-PVC membrane, despite its lightness, is the primary contributor to most environmental impact categories, including GWP, Ozone Depletion Potential (ODP), and Acidification Potential (AP), due to its significant material and energy demands. Aluminum profiles, while having a smaller overall footprint, show a notable impact on resource-related categories such as Abiotic Depletion Potential for Elements (ADPE), reflecting the resource-intensive nature of

Material	Quantity	Km of transport	Service life	End of life treatment
PES-PVC membrane	0.51 kg	430	15 years	Plastic-based material incineration
Steel fastening systems	0.52 kg	370	As building	Steel recycling
Aluminum profiles	2.1 kg	470	As building	Aluminum recycling

Table 2.
Life cycle inventory of textile cladding solution.

aluminum production. In contrast, fastening systems have a minimal influence across all categories, indicating their relatively minor role in the overall environmental burden. It should be noted that the software does not account for the recycling phase's impact; however, during the A1–A3 phases, it assumes the same production processes as those required for primary materials. Primary energy use (PERT and PENRT) and water use are predominantly driven by the PES-PVC membrane, emphasizing its critical role in the system's sustainability.

These findings highlight the need for material optimization, particularly for the PES-PVC membrane, and the potential benefits of using recycled aluminum to reduce ADPE. Additionally, while their impact is small, exploring alternative fastening systems could provide incremental improvements to the system's overall environmental performance.

4.3 LCA of aluminum cladding solution

4.3.1 Data collection and assessment

The option of aluminum perforated panels as a cladding system foresees the use of perforated metal sheets with a specific percentage of perforation in order to resemble as much as possible the choices adopted in the membrane case. Aluminum perforated metal sheets, in addition to their aesthetical pleasantness and their ease of production and fabrication, are very light, therefore representing a favorable material for cladding applications, particularly when weight is an important parameter. Additionally, they can be almost entirely recyclable, and the use of a recycled material can be foreseen even in a retrofit strategy.

Analogously to the textile cladding solution, the quantities for the substructure have been derived based on the research conducted by Procaccini & Monticelli [41]: the amount of substructure for supporting the perforated aluminum panels accounted for almost 3 times more than in the case of the membrane, due to the additional weight but specifically due to the fixed dimensions of the aluminum panels, which contrasts with the tensioning capability of the membrane that allows for a great span covering.

The aluminum sheets considered in this analysis have a thickness of only 2 mm and a weight of 8.5 kg/m^2. These panels are supported by a frame of vertical and horizontal aluminum profiles that account for 6.3 kg (**Table 3**). In contrast with the previous cladding solutions, the aluminum cladding does not require any fastening system for fixing the sheets to the substructure.

4.3.2 Results

The LCA results for the Aluminum Cladding Solution represented in **Figure 9** indicate that aluminum gratings are the primary contributors to the environmental

Material	Quantity	Km of transport	Service life	End of life treatment
Aluminum gratings	8.5 kg	470	As building	Aluminum recycling
Aluminum profiles	6.3 kg	470	As building	Aluminum recycling

Table 3.
Life cycle inventory of aluminum cladding solution.

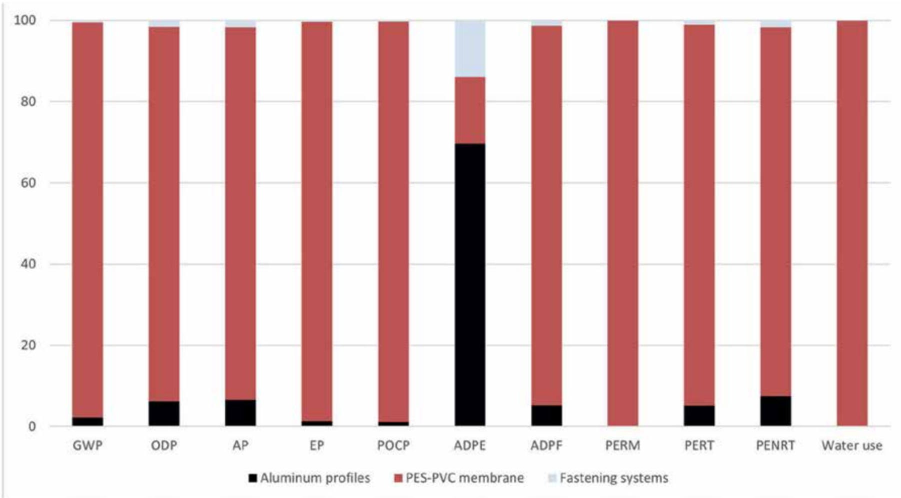

Figure 9.
Aluminum cladding solution: environmental impacts of cladding material and its substructure.

impact across most categories, such as GWP, AP, PERT, and PENRT, underscoring the material resource-intensive production and its energy demands. While the aluminum profiles have a smaller overall impact, they show a notable influence on Abiotic Depletion Potential for Elements (ADPE), reflecting the significant resource extraction required for their production.

Additionally, water use and Ozone Depletion Potential (ODP) are also largely driven by the aluminum gratings, further emphasizing their role as the dominant factor in the system's environmental burden. Despite their relatively lower contribution, aluminum profiles still merit consideration, particularly in categories related to material scarcity and resource depletion. These findings point to the critical need for design improvements and material substitutions, such as incorporating recycled aluminum or optimizing material usage, to minimize the environmental footprint of both aluminum gratings and profiles in cladding systems.

4.4 Final consideration

The comparative analysis reveals a significant disparity in environmental impacts (**Figure 10**). The aluminum cladding system exhibits significantly higher impacts across most categories, reflecting the energy-intensive processes associated with the raw material extraction and production processes. In contrast, PES-PVC cladding, due to its lightness, has minimal impacts for both these stages, although it still exhibits a notable impact on the Abiotic Depletion Potential for Elements (ADPE), likely linked to its reliance on specific raw materials and production techniques.

Furthermore, the ratio of the envelope's weight to that of the substructure (Principle 2) is 0.19 for the Textile Cladding Strategy and 1.35 for the Aluminum Cladding Solution. This metric emphasizes the importance of considering both structural and material aspects in façade design to achieve optimal eco-efficiency.

Overall, the PES-PVC cladding solution stands out as a more sustainable alternative, particularly in terms of reducing energy demand and emissions, making it a suitable choice for eco-conscious façade retrofit applications (**Figure 11**).

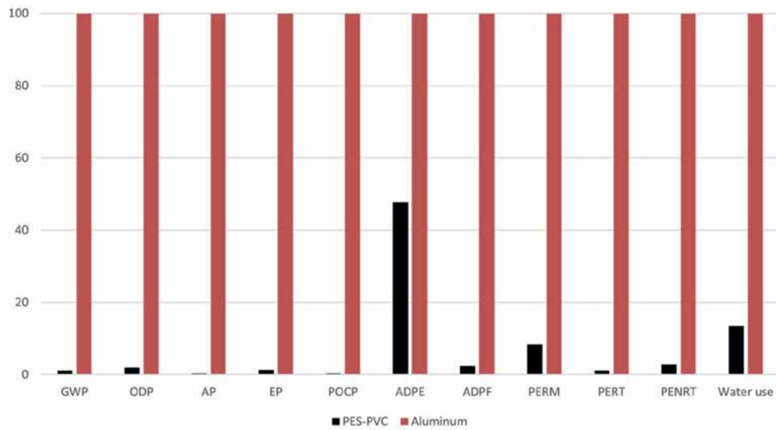

Figure 10.
Comparison between the environmental impacts of the textile cladding solution and the aluminum cladding one.

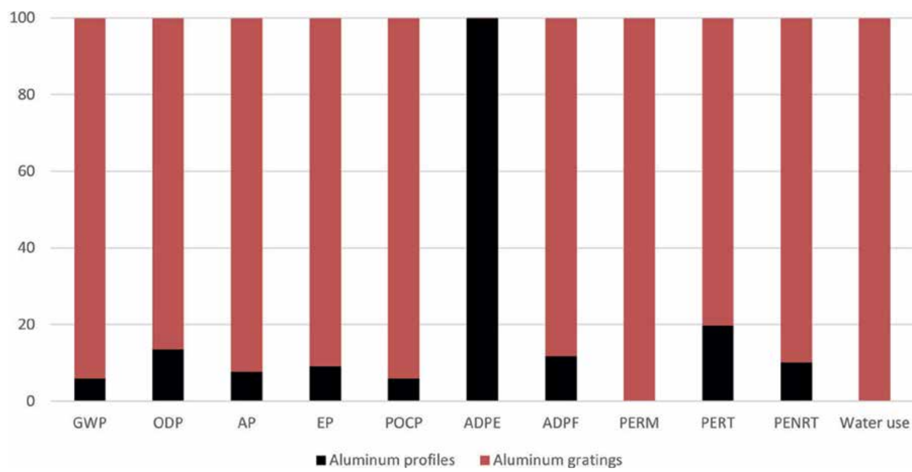

Figure 11.
Textile cladding solution: Environmental impacts of cladding material and its substructure.

5. Conclusion

This chapter analyzed alternative retrofitting solutions based on two construction paradigms of energy efficiency, namely the reuse of secondary streams for bio-based material applications and material reduction through the adoption of lightweight building systems. The findings are intended to help manufacturers optimize their products and support designers in making informed decisions during the design phase to identify opportunities for reducing the overall environmental footprint of façade retrofit systems.

Strategies adopting insulation panels made of recycled materials and bio-materials have both lower GWP than conventional materials and good thermal performances. Additionally, the impacts associated with the production of mycelium composites could still improve, as mentioned above, if scaled at the industrial level. In this regard, although conventional materials and foams such as EPS and polyurethane (PU) are still predominant in the market, different companies, such as RiceHouse (https://www.ricehouse.it/), Strawcture (https://strawcture.com/), ProSuber (https://www.prosuber.com/) and Mogu specifically for mycelium composites, (https://mogu.bio/), are paving the way towards the wider commercialization of bio-based thermal and acoustic insulation panels.

However, to achieve more extensive application and market penetration, further investigations on the adoption of insulation panels made of recycled materials and bio-materials might regard:

1. The investigation of EoL scenarios for insulation composites made of recycled textiles;

2. The formulation of a shared protocol to assess the associated metabolic carbon of mycelium, which might lower the final carbon storage of the produced composite;

3. The industrial scalability of the mycelium technology;

4. The feedstock availability for the agro-residues, affected by cultivation seasonality

5. The application of both strategies on real-case studies to analyze their durability in the long run;

6. The standardization of bio-panels for building applications to reach standards of durability and fireproofing.

Conversely, lightweight solutions highlight how reducing material usage and consequently minimizing substructure requirements can substantially lower the environmental footprint of retrofit strategies during the pre-use phase. Indeed, although often underrepresented for retrofit interventions, textile membranes can integrate energy efficiency, material substructure recyclability, and streamlining. However, assessing aspects such as their durability, ranging from 10 to 30 years depending on materials' composition and manufacturing processes, and EoL treatments, at the moment mostly involving plastic incineration, is fundamental to determine a complete LCA. In this regard, alternative EoL treatments for plastic reuse or recycling would further enhance the final net-benefit of each retrofitting textile strategy.

Acknowledgements

This study was funded by the European Union's Horizon Europe research & innovation program under the HORIZON-MSCA-2021-DN-01 grant agreement No. 101072598 – "ActaReBuild", by the European Union - NextGenerationEU, in the framework of the MICS - Made in Italy Circolare e Sostenibile project (MICS PE00000004 – CUP 43C22003120001) and by Politecnico di Milano - maTE.ria - Metodi e Azioni per il Trattamento Ecologico dei Tessili post-consumo e il loro Riciclo Innovativo in Architettura – under the initiative of Ministero dell'Ambiente e della Sicurezza Energetica.

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Chapter 9

Hybrid Mini-Grid Solutions to Rural Energy Poverty: Toward Sustainable Energy Access and Socioeconomic Impacts in the Upper Blinkwater Community, South Africa

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Abstract

Energy poverty continues to affect millions of rural South Africans, limiting opportunities for socioeconomic development. Amid the country's ongoing struggle to meet its growing energy demands, emerging renewable energy technologies, particularly off-grid hybrid mini-grids, have gained recognition as sustainable and practical solutions. This study evaluates the effectiveness of hybrid mini-grid renewable energy systems in mitigating energy poverty in the remote Upper Blinkwater community. Specifically, it investigates how these systems reduce dependency on traditional fuels, enhance energy access, and improve household-level socioeconomic conditions. Using qualitative and quantitative analyses of survey data collected before and after mini-grid deployment, the findings reveal a substantial decline in per capita energy expenditure, indicating a significant reduction in the proportion of energy-poor households due to access to affordable and reliable electricity. The results also demonstrate improvements in household modernization, with increased adoption of modern appliances such as refrigerators, electric kettles, and washing machines, which have significantly reduced domestic labor, particularly for women. Additionally, the mini-grid facilitated the establishment of new income-generating activities, many of which are owned and operated by women, leading to diversified livelihoods and enhanced gender equity. The study further highlights health benefits, including better adherence to treatment for individuals with chronic illnesses due to timely meal preparation and secure medication storage enabled by electrification. These findings underscore the transformative role of mini-grids in alleviating energy poverty, improving quality of life, and fostering sustainable socioeconomic development in rural South Africa.

Keywords: energy access, energy poverty, off-grid mini-grids, quality of life, socioeconomic impacts, sustainable energy solutions

1. Introduction

Energy poverty has remained South Africa's major concern, with rural and isolated areas struggling to get access to stable electric power. Despite having the highest electrification level in the Sub-Saharan African region, with 86% [1] being connected to the grid, including 85% of rural areas, many households in South Africa remain energy-poor. Around 14% of the population and 15% of rural households lack access to the grid, indicating an ongoing failure in equitable energy access. Disconnects are widespread, particularly impacting remote communities and continuing cycles of energy poverty while stunting socioeconomic development and widening the urban-rural divide. For instance, studies such as Ngarava et al. [2] highlight how energy poverty exacerbates economic inequality in South Africa, demonstrating a strong link between lack of energy access and broader issues of poverty and inequality. Households without access to modern energy services often rely on traditional fuels like firewood and charcoal, which have adverse health effects [3] and disproportionately impact women, who bear the brunt of energy poverty. Women are often responsible for collecting firewood and cooking, tasks that are both time-consuming and physically demanding [2, 4]. Longe [1] further emphasizes that the time spent on these daily responsibilities reduces women's opportunities for education, income-generating activities, and community participation.

Energy poverty, however, is not merely about the lack of electricity. Even with grid access, many households face affordability challenges, with approximately 43% allocating a significant portion of their income to electricity costs, highlighting the multi-dimensional nature of energy poverty [3, 5]. Overall, according to several definitions, more than half of the South African population is susceptible to energy poverty, indicating the persistent inequalities in energy access [6]. These challenges are further compounded by supply constraints and rising energy demand, which intensify South Africa's energy crisis and make achieving universal access more difficult [7]. Reasons such as geographical isolation, sparse population, and low household income make it prohibitively expensive for the national utility (Eskom) to extend grid infrastructure to remote areas [8, 9].

Despite the National Development Plan (NDP) forecasting that 95% of South Africans will have access to electricity by 2030 and a target of 66% access to grid power [10, 11], this has not yet been achieved owing to these constraints. In remote rural areas where it is uneconomic to expand electrification infrastructure, it is unlikely to address the problem [8]. Renewable energy technologies, particularly off-grid mini-grids, are gaining recognition as viable solutions for addressing energy poverty in remote rural areas where grid extension is economically unfeasible [12]. Not only do these solutions align with the NDP's vision of universal access, but they also seem to be in line with South Africa's goals for an energy transition. It was estimated that renewable energy, such as solar and wind, will be used more than 10 times in 2030 than they are now and that fossil fuel use will drastically decline [13].

Literature also suggests that renewable energy not only provides reliable and affordable energy but is also a transformative tool for socioeconomic growth, especially in disadvantaged communities [14]. Mini-grids have the potential to alleviate poverty by enabling the productive uses of energy, such as supporting small businesses [15] and improving access to basic services, which can generate income for rural communities and provide particular benefits for women [16, 17]. Although electricity alone may not create all the conditions necessary for economic growth, it is undeniably essential for meeting basic human needs and supporting economic activity [18].

Estimates indicate that expanded energy access to renewable energy could lead to an increase of up to 1.1% of global GDP along with significant gains in employment and welfare by 2030 [14, 19]. This highlights the potential for significant benefits, including welfare improvements, from investments in energy access, especially in developing nations like South Africa. Yet, although mini-grids are emerging as promising solutions to energy poverty, in South Africa, their implementation has had mixed success. Only a few community-based mini-grids have been deployed, and many of these have faced challenges. Issues such as maintenance, community engagement, and financial sustainability have often undermined their effectiveness [20]. For instance, projects like the Hluleka Nature Reserve and Lucingweni mini-grids failed to achieve their intended goals due to system inefficiencies and operational shortcomings [21, 22].

In contrast, the Upper Blinkwater hybrid mini-grid project stands out as a groundbreaking initiative addressing energy poverty in a remote rural community in the Eastern Cape Province. This project was developed to mitigate long-standing energy deprivation and exemplifies a sustainable and viable energy solution tailored to rural needs. Supported by the German government and the Federal State Pilot Program (Bund-Länder-Programm; BLP), in collaboration with Lower Saxony and the Eastern Cape Provincial Government, through its various departments and stakeholder agencies, the initiative successfully electrified 67 households, delivering a reliable energy supply a decade ahead of schedule [23]. Its success signifies the transformative potential of hybrid mini-grids to alleviate energy poverty and improve livelihoods in marginalized areas [24]. However, despite its successful implementation, there is a lack of scholarly evidence assessing whether the mini-grid has effectively alleviated energy poverty among households in this community. This study aims to address this gap by evaluating the impact of the Upper Blinkwater hybrid mini-grid project, emphasizing that access to electricity is crucial for improving living conditions. In addition to examining energy access, the study also evaluates the social impacts of the mini-grid, recognizing that the broader social effects are an integral part of the success of such systems. The findings will contribute to the growing body of literature on off-grid energy access, energy poverty alleviation, and sustainable development. This analysis is set to inform policy decision-makers, development practitioners, and researchers, offering valuable insights into the potential of hybrid mini-grids as a tool for alleviating energy poverty and fostering socioeconomic transformation in South Africa.

The rest of this chapter is organized as follows: Section 2 provides an overview of mini-grids in South Africa. Section 3 describes the methods used in the study. The presentation and discussion of the findings are in Section 4, and Section 5 provide the discussion of the findings. Section 6 provides the conclusion and recommendations to scale similar interventions in different rural areas.

2. Overview of hybrid mini-grids in South Africa

Mini-grid systems are generally defined as autonomous, localized energy systems that generate, store, and distribute electricity to a small geographic area or community, operating independently from the national electricity grid. They are also referred to as decentralized utilities or off-grid electricity distribution networks. While there is no universally accepted definition, mini-grids are typically characterized by their generation capacity, which ranges from as low as 1 kW to a maximum of 15 MW [7, 25–27]. These systems are particularly ideal for remote or off-grid locations where they can manage local supply and demand effectively.

For this study, we focus on hybrid mini-grids that utilize solar photovoltaic (PV) and wind energy technologies. These systems are designed to take advantage of the complementary characteristics of solar and wind resources, providing a more reliable, clean, cost-effective energy source and continuous energy supply while addressing the issue of energy poverty robustly [23]. For instance, solar energy production peaks during the daytime, while wind energy can be generated at night or when solar output is low, depending on local wind conditions. Hybrid systems often incorporate battery storage to retain surplus power generated during peak production times, enhancing reliability. This stored energy can then be used during periods of low generation, such as at night or during times of insufficient sunlight or wind. In exceptional circumstances, diesel generators may serve as a backup for these hybrid mini-grids [28–30].

However, hybrid mini-grids are still a relatively new concept in South Africa, emerging as a response to the limitations of centralized grid expansion in effectively addressing energy access in remote, sparsely populated areas. Prior to the 1990s, South African electrification efforts were focused on expanding the national grid, neglecting off-grid solutions. During the early days of the national electrification program in the 1990s, it became clear that urban residents were benefiting disproportionately and that rural residents and villages were lagging behind due to logistical and financial constraints toward grid connection [22, 31]. This disparity prompted the government to explore decentralized energy systems, such as launching the Solar Home System (SHS) program.

The SHS program was piloted in provinces such as the Eastern Cape and KwaZulu-Natal and successfully electrified more than 20,000 rural households, demonstrating the viability of solar photovoltaic (PV) systems for energy access. However, while SHS systems have served rural households for over a decade, their inability to meet larger energy demands led to the exploration of more robust solutions, such as renewable energy hybrid mini-grids [27]. Hybrid mini-grids typically combine two or more renewable energy sources (such as PV, wind, micro-hydro, storage batteries, and fuel-powered generators), enabling them to support higher energy loads and deliver more reliable access to energy. Their key advantage also lies in aligning with the goals of South Africa's Integrated Energy Plan (IEP), which seeks to balance energy demand with supply resources while addressing safety, health, affordability, and environmental sustainability.

Two pilot hybrid mini-grid systems were constructed in the Eastern Cape: one at the Hluleka Nature Reserve and the other in the nearby Lucingweni community. The Hluleka system integrated wind generators and solar PV modules to meet the energy, water purification, and telecommunication needs of the nature reserve. However, the project faced serious challenges, including high energy consumption, inefficient operation, and an overreliance on diesel generators [11, 20]. The Lucingweni mini-grid, on the other hand, was launched to demonstrate the suitability of hybrid mini-grid energy systems for rural communities in close proximity to the Hluleka Nature Reserve, but it was disbanded just 3 months after its commissioning. Some of the key issues included frequent vandalism resulting in significant damage to property, unmet expectations, operational problems, and poor communication [31]. It emerged later that the project had been executed with very little community involvement. Consequently, it was thought that the community saw the mini-grid rollout as a hindrance to the future expansion of the national grid. These shortcomings underscored the importance of community engagement and affordability in planning energy projects [22, 32]. Hluleka on the other hand, never operated at maximum efficiency. Although it was designed as a solar-wind-diesel hybrid, it quickly became entirely diesel-powered [33]. From a performance and energy access point of view, it is safe to say that the two mini-grids never really performed well. Subsequently, all proposed mini-grid projects were aborted following feasibility assessments [31].

These setbacks prompted advancements in renewable energy technologies and improved policy frameworks with renewed interest in hybrid mini-grids in South Africa. Unlike earlier initiatives, the recent implementation of the hybrid mini-grid in Upper Blinkwater was designed with a focus on community engagement, informed by lessons learned from previous failures. This project exemplifies how the integration of technical expertise and community involvement can sustainably address rural energy poverty [21].

This study, therefore, aims to provide evidence-based insights into the effectiveness of the Upper Blinkwater hybrid mini-grid in reducing energy poverty and improving the quality of life in off-grid communities. Drawing from field data and community feedback, it seeks to evaluate whether such initiatives can justify investments in hybrid mini-grids as a viable solution. This research is significant not only because it documents the tangible changes brought about by the Upper Blinkwater project, but also because it has the potential to serve as a benchmark for future government efforts to expand access to basic resources and foster a more equitable and harmonious living environment in historically marginalized communities.

3. Methodology

3.1 Description of the study area

The study was carried out in the Upper Blinkwater community, a remote, small rural community in the Raymond Mhlaba Municipality. Upper Blinkwater is located at an altitude of about 900 m above sea level, and the coordinates are 32°34′46.7′′ S and 26°33′33.8′′ E; the municipality mainly relies on agricultural activities such as citrus, forestry, livestock, and cropping [34]. With its dispersed settlements, Raymond Mhlaba is faced with major problems, including poor infrastructure and low accessibility. These factors lead to extreme poverty and a high unemployment rate, with most households relying on social grants as the main source of income. Upper Blinkwater is made up of only 67 households, mainly of Xhosa and Afrikaans origin with about 254 people in total. This community was chosen as the focus of the study as it was the first identified beneficiary of a renewable energy pilot project to implement a hybrid mini-grid seeking to address rural electrification challenges in South Africa. **Figure 1** shows the location of the Upper Blinkwater community and the Raymond Mhlaba municipality location in the Province of the Eastern Cape.

3.2 Sampling

Upper Blinkwater consists of only 67 households [36, 38], making it challenging to obtain a representative sample due to the small population size. Sample size classes of this magnitude often result in even smaller samples, further limiting the generalizability of any conclusions drawn [39]. To address this limitation, Korngiebel et al. [39] recommend assessing the entire population to reduce distortion in the findings. Following this recommendation, all 67 households in Upper Blinkwater were considered eligible for the survey. However, due to availability constraints, interviews were conducted with 53 heads of household.

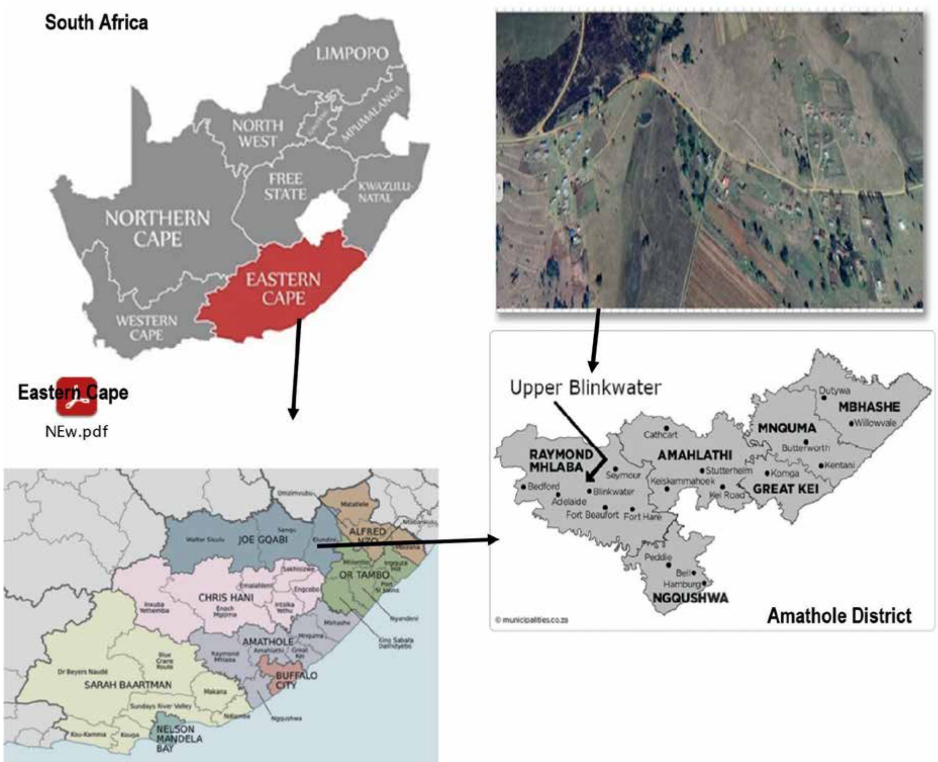

Figure 1.
Upper Blinkwater location. Source: [35–37].

3.3 Data collection and analysis

Data for this study was collected at two critical intervals: the baseline in 2019 and a follow-up in 2021, 2 years after the installation of the hybrid mini-grid. The baseline survey collected data on energy use and expenditure patterns associated with traditional energy sources prior to the mini-grid installation. It also examined key socioeconomic indicators such as household income, education levels, and employment status, providing a foundation for comparison. After the mini-grid installation, the follow-up survey was expanded to include questions focused on the adoption of household appliances and the community's perceptions of the mini-grid electricity. These questions explored the reliability, affordability, and accessibility of the new energy source, as well as its perceived impacts, including their satisfaction with how the electricity supply influenced their daily lives and overall well-being.

Interviews were conducted with the assistance of local community members who translated the questions into the local language and clarified them for respondents to minimize misunderstandings. This approach facilitated the collection of both quantitative and qualitative data, providing a nuanced picture of how enhanced energy access affected household dynamics and overall well-being. A pre-and post-intervention data collection methodology was adopted to create a robust dataset capable of evaluating changes in energy spending patterns and community quality of life.

The quantitative analysis compared pre- and post-implementation energy expenditures to assess whether the hybrid mini-grid resulted in significant expenditure reduction for households. Energy expenditure per capita served as a primary metric for measuring energy poverty; socioeconomic indicators, such as household income and employment levels, were also analyzed to explore whether improved energy access generated additional economic benefits.

The qualitative analysis provides context illustrating where improved energy access translated into measurable social and economic gains. It involved responses to open-ended survey questions, which captured households' perceptions of the mini-grid energy, and quality of life improvements.

4. Findings

4.1 Analysis of socioeconomic status of Upper Blinkwater households

The socioeconomic conditions of Upper Blinkwater reflect significant energy poverty and limited economic opportunities. Employment trends show a high rate of unemployment, with 45% of respondents unemployed, which highlights the lack of job opportunities in the area. Most households in the community are dependent on social grants, with child grants being the largest contributor to household income, indicating that many households are in financial distress with low or no income from employment. The average household income is quite low, averaging ZAR 2321.90 (USD 127.62). Despite the challenges, there is little opportunity for households to diversify income streams or create small businesses due to the lack of reliable energy sources. The introduction of the hybrid mini-grid brought some changes to the community's socioeconomic conditions, though many challenges remain. Unemployment continues to be a major issue, with the rate rising to 59%. While the mini-grid likely helped ease some of the energy burdens, it did not directly address the widespread issue of unemployment, indicating that access to energy alone is insufficient to stimulate significant job creation in the community. However, there was an increase in self-employment, rising from 6% to 11%. This suggests that improved access to energy may have allowed for the development of small businesses, particularly those that require energy-intensive activities. Despite this, the overall economic impact remained modest, as self-employment did not dramatically change the community's financial situation. Social grants remain a major contributor to household income, particularly child grants, reflecting the ongoing reliance on government support. The average household income is slightly higher, ranging from ZAR 2321.90 (USD 127.62) to ZAR 2710 (USD 148.35), but it remains very low compared to broader national standards.

Overall, the socioeconomic conditions in Upper Blinkwater show modest improvements, with a slight increase in self-employment. However, unemployment and dependence on social grants remain high, indicating that while energy access is an important factor in improving quality of life, it alone is not enough to drive significant economic development in such marginalized communities (**Table 1**).

4.2 Energy access and reduction in energy expenditure

Before the introduction of the mini-grid, households in Upper Blinkwater primarily relied on traditional energy sources such as firewood, paraffin, LPG, and candles for their daily energy needs. Among these, firewood was the dominant source of energy, used by nearly all households for cooking and heating. Paraffin and LPG were also commonly used for lighting and cooking, while candles were occasionally used

Indicator		Before mini-grid (%)	After mini-grid (%)
Gender of household head	Male	55	32
	Female	45	68
Employment status	Not employed	45	59
	Employed	23	11
	Self-employed	6	11
	Retired/pensioner	26	19
Main source of income	No income	15	13
	Salary	26	18
	Own business	6	14
	Grant	69	50
	Remittance	17	5
Average household income		ZAR 2046	ZAR 2710

1 USD = 18.2 ZAR.

Table 1.
Socioeconomic factors before and after mini-grid implementation.

for lighting during the evenings. These energy sources came with their own set of costs and inefficiencies, contributing to the energy burden of households. With the adoption of the mini-grid, electricity became a new energy option for the community, replacing some of these traditional sources. However, almost all households continued using firewood, some LPG, and paraffin. Nonetheless, the shift toward electricity brought notable changes to energy expenditure patterns. Households began to spend an average of ZAR 69.52 (USD 3.82) per month on electricity while spending on wood and LPG showed only a slight decline; the use of paraffin and candles dropped significantly, indicating that the mini-grid effectively replaced these more traditional energy sources. However, some households continued using wood, LPG, and paraffin, suggesting that the transition to electricity was not yet complete. The total energy expenditure also decreased marginally from ZAR 247.75 (USD 13.61) to ZAR 242.30 (USD 13.34), reflecting a small overall reduction of 2.2%. This suggests that the introduction of electricity costs did not significantly raise the total energy spending for households. Instead, the more efficient mini-grid likely displaced more expensive or less energy-efficient energy sources like paraffin, wood, and candles, leading to overall savings. Otherwise, the per capita energy expenditure also saw a notable reduction, from ZAR 92.40 (USD 5.08) to ZAR 60.70 (USD 3.34), representing a 34.3% decrease. This decline implies the economic benefits of replacing traditional energy sources with mini-grid electricity, significantly reducing the energy burden per individual. This shift suggests an improvement in the affordability of energy for households, a crucial factor in addressing energy poverty and supporting economic well-being in the community.

4.3 Adoption of appliances and modernization

In terms of the impacts the mini-grid has had on the community, besides that household energy spending has reduced significantly as shown in **Figure 2**, the findings revealed that electrification has turned out to be more than a way to save on

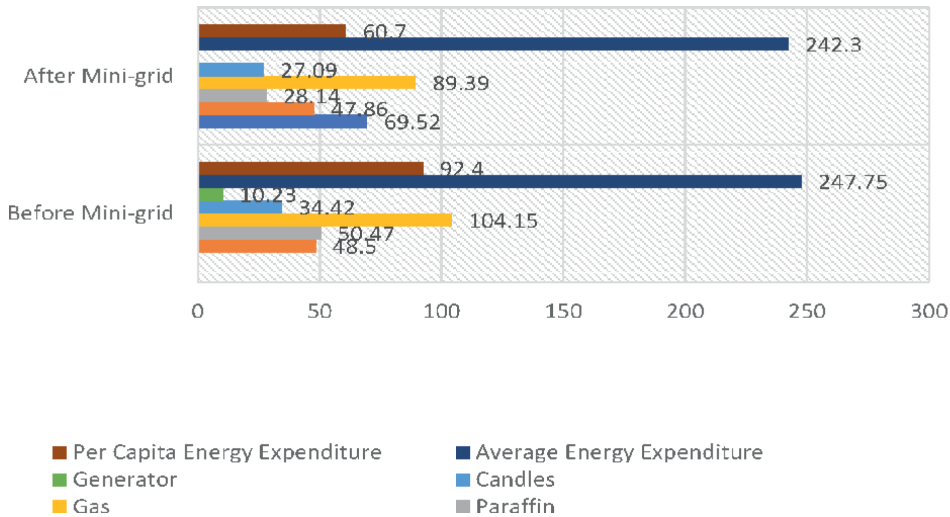

Figure 2.
Summary statistics on energy expenditures in ZAR.

costs but a modernization of daily life in transformative ways. Access to electricity has afforded families and the society, to have better lighting and use other electrical devices. Before the mini-grid, household appliances in this community were rare. For those who had, for example, a television;

"*Televisions, were for decoration as we hope that one day we will be able to watch it.*" Indicated one of the respondents, as another one added they depended on primitive heating and cooking devices. However, the introduction of the mini-grid electricity brought modern appliances such as refrigerators, electric cooking stoves, washing machines, televisions, and phone charging. Not only have these innovations transformed home chores, but they have also enhanced the community's quality of life significantly and provided comforts that once seemed out of reach. For instance, **Figure 3** illustrates one respondent demonstrating the use of an electric appliance for boiling water and cooking, showcasing the practical benefits of electrification. Another respondent highlighted how their living room had been improved and better furnished, thanks to access to electricity.

Figure 3.
Evidence of mini-grid impact on household energy use.

4.4 Livelihood activities and income generation

The mini-grid has also contributed positively to livelihood activities through job creation, specifically during the construction phase. A total of 18 community members were employed, including 16 men and 2 women, in roles such as clearing vegetation, excavating foundations, and providing site security. Although these positions were temporary, they offered valuable income and skills development, and one permanent job opportunity was created for one youth member who was trained as a technician to oversee system maintenance. In addition to direct employment, the project created indirect income opportunities for community members through house rentals. Construction workers rented four houses in the community, while an additional house was rented as a storage facility for construction equipment. These rental agreements provided supplementary income for local households, further contributing to the community's economic upliftment during the project.

Previously, it was harder for people in this community to do business, especially trading items that require refrigeration. But with electricity, a number of income-generating activities were established; one is a woodwork workshop that makes furniture, which uses mini-grid power for cutting and welding iron and steel. There are also some small household business activities, like trading soft drinks and foodstuffs like meat, which need refrigeration, most of which are run by women.

The electrification brought by the mini-grid has significantly contributed to the development of small-scale crop farming in the community. Some of them have long been practicing farming under limited circumstances due to water scarcity. One of the respondents has demonstrated how using an electric water pump powered by the mini-grid energy for irrigation in his small plot has helped in increasing his yields and even encouraging him to expand. The respondent grows a range of vegetable crops, including maize, cabbages, and potatoes, alongside high-demand produce like watermelon, which they sell almost daily. This has allowed the farmers to increase their yields and subsequently report seasonal earnings as high as ZAR 12,000 (USD 640) per month. Additionally, electrification has enabled farmers to diversify into microenterprises, such as poultry farming, providing supplementary income and fostering local economic growth.

4.5 Health impacts

Health impacts of the mini-grid have been largely focused on improving the lives of people with chronic diseases. A major improvement has been seen in the timely administration of medication. When you found it difficult with chronic conditions to prepare a meal before taking your medicine by first collecting firewood and boiling water, it took time. With electricity, they can boil water to prepare meals faster and take their medications more timely using an electric kettle. Moreover, several drugs need refrigeration for proper storage, but with a mini-grid in place, respondents can keep their medications safe and effective during treatment. Timely preparation of meals and storage of medication in the presence of such automation has been shown to improve adherence to treatment and have positive effects on the health of people suffering from chronic illnesses, supporting their overall health outcomes.

4.6 Community perception of mini-grid electricity

The community perception of the mini-grid in Upper Blinkwater was analyzed in terms of accessibility, reliability, and affordability. Most respondents expressed positive views on accessibility, with the majority having mini-grid panels and electricity meters installed in their homes. The mini-grid electricity was also praised for its reliability, with residents emphasizing its stability and the absence of load shedding, which has rocked the country for a long time.

"*The electricity is very reliable. We do not experience blackouts, and I have no complaints*," one respondent noted.

However, the weather's impact was a recurring concern, with some mentioning that on cloudy or rainy days, electricity could be interrupted. As one respondent commented,

> *"Even though we know that on rainy days we will experience some problems, we understand it's because of the weather."*

In terms of affordability, many respondents found the cost of mini-grid electricity reasonable compared to traditional energy sources. One participant shared,

> *"Before the mini-grid electricity, I used to spend between R100 and R250 monthly for paraffin, which is more expensive than the once-off R200 I spend now on electricity prepaid that lasts me the whole month."*

Others mentioned that affordability depended on disciplined energy use, with one noting,

> *"The electricity is reasonably priced. It comes with discipline on how you use your appliances, and in that way, you can save a lot of money."*

However, larger households and those with higher energy needs found the electricity less affordable. One respondent expressed,

"*For me, the electricity prepaid is very expensive. I live on my child support grant, and the prepaid electricity doesn't last the whole month.*" Another shared, "*I live in a family of five, and our energy needs are high. I spend about R200 monthly, which doesn't feel cheap.*"

These responses highlight that while the mini-grid is generally viewed as an improvement, affordability remains a concern that varies depending on household size, income levels, and energy usage patterns, reflecting the economic inequalities that persist within the community. Despite these challenges, the mini-grid is widely regarded as a transformative initiative that has significantly improved the quality of life for many households.

Respondents expressed feeling a sense of inclusion and progress, finally experiencing the benefits of being part of a democratic South Africa. The majority reported satisfaction with the accessibility and reliability of the electricity provided, emphasizing the convenience it brought to daily activities like cooking, ironing, and lighting. For many, the mini-grid has reduced their reliance on traditional energy sources such as paraffin and gas, which were both less efficient and more expensive. Some households even noted that they no longer needed to purchase these fuels, which marked a significant financial relief and improved living conditions. Overall, the community's acceptance of the mini-grid underscores its positive impact and alignment with its intended purpose.

5. Discussion

This study highlights the transformative impacts of mini-grids on energy access, household modernization, livelihood activities, and community well-being. The introduction of mini-grids has significantly improved energy access in the Upper Blinkwater community, replacing traditional energy sources like firewood, gas, paraffin, and candles with cleaner, safer electricity. However, firewood continues to be the primary energy source for cooking and heating. This result reaffirms [40] the assertion that even with an electricity connection, rural households would continue using firewood, mainly because for some, firewood is readily available and affordable. Rossella and Grazia and Sovacool and Griffiths [41, 42], on the other hand, attribute this behavior pattern to traditional and cultural practices passed down through generations, including maintaining food flavor or taste [3]. Therefore, regardless of their financial stability, they continue using firewood. Nonetheless, the adoption of mini-grid electricity has reduced reliance on using paraffin and LPG, which does confirm that renewable energies are the cheapest sources of electricity compared to the conventional energy sources [43].

The most notable impact of mini-grid electrification in Upper Blinkwater is the decrease in households' energy expenses. This shift results in a lower cost of energy on a per capita basis, representing substantial savings compared to expenditures on conventional energy sources. This suggests that mini-grids not only displace costly and inefficient energy options but also lower household energy expenditures, thus preserving income, which can then be redirected toward meeting other essential needs. These findings are substantiated by Babalola et al. [26], who also found out that in Nigeria, the microentrepreneurs' energy expenditure declined by half (50%) upon mini-grid connection, compared to when households depended on self-generated energy. Thus, highlighting the economic advantages of adopting more efficient energy systems. Additionally, the availability of electricity has allowed households to adopt modern appliances, such as refrigerators, electric stoves, kettles, televisions, and washing machines. These appliances have not only improved daily life but also reduced the physical burden and time spent on tasks like food preparations, especially for women, freeing up time for other activities. This corroborates studies that show how electrification reduces the time spent on domestic work, increasing household productivity [44].

The mini-grid has also enabled the establishment of small businesses, which in turn contributes to livelihood improvement activities. For example, furniture workshops and small food enterprises use small fridges powered by the mini-grid. Some of which are run by women, showcasing how electrification can empower women entrepreneurs. This finding aligns with research that highlights the role of electricity in promoting gender equity by enabling women's participation in economic activities [45]. According to the United Nations (UN) [46], this is due to their increased productivity because of using appliances, which frees them from housework, enabling them to have free time for income-generating activities. In addition, access to electricity can also improve women's decision-making ability, their financial autonomy, and provide them reproductive freedom, which will likely reduce fertility rates, often due to increased labor market participation [46].

One of the notable economic benefits of the mini-grid was the creation of employment opportunities during the construction phase, where community members were employed in unskilled and semi-skilled roles. Mostly, the youth benefited from these temporary positions, which provided valuable income and experience. Importantly, the skills development and training provided before the implementation had a lasting impact, as one youth member highlighted how such initiatives can open doors to long-term opportunities and community empowerment. This has been confirmed by similar projects such as those implemented in Lesotho, where community members not only benefit from electrification but also through employment and rental of their homes [17].

The mini-grid had also significantly contributed to agricultural production and productivity. Small-scale farmers in the community of Upper Blinkwater can now use electric water pumps for irrigation, enhancing their agricultural production and productivity. This has led to increased scale of production of one of the respondents and increased crop yields surplus production, which created more opportunities for commercialization, ultimately improving household income and contributing to food security. As Pawlak and Kołodziejczak [47] suggest, enhanced agricultural productivity plays a strategic role in improving food availability and achieving food security. This, in turn, serves as a key driver for income generation and an improved quality of life in rural areas. These findings align with Ayhan et al. [48], who found positive effects of mini-grid electrification on local agricultural output in Sub-Saharan Africa, especially vegetables, in the cropland surrounding the community served by the mini-grid. This thus implies that the mini-grid electrification increases both the probability and productivity in crop farming.

Mini-grid electrification has also brought significant health benefits, particularly for individuals with chronic diseases. Before electrification, those with chronic conditions faced difficulties in preparing meals and taking their medication on time due to the need to gather firewood and boil water. The introduction of electricity has enabled more efficient meal preparation, using an electric kettle, enabling people to adhere to their medication schedules. Additionally, the mini-grid has facilitated the proper storage of temperature-sensitive medications, ensuring their potency and effectiveness during treatment, leading to positive health outcomes.

The response from the community has been overwhelmingly positive, with residents expressing a sense of relief and joy due to the improved electricity supply. The mini-grid's resilience to load-shedding challenges, which have affected the national grid, has been particularly valued. This stability and independence in energy supply have contributed significantly to the community's satisfaction with the project. These findings reflect the growing recognition of the importance of reliable, sustainable energy solutions, such as mini-grids, in reducing vulnerability to energy disruptions and providing energy security.

In terms of community perceptions, accessibility, reliability, and affordability were the most significant factors, which, according to Bouzarovski and Petrova [49], form part of the six key indicators for assessing households' vulnerability to energy poverty. Based on the findings, accessibility and reliability of the mini-grid energy were widely praised, with most respondents expressing satisfaction with the consistent power supply and convenience provided by the mini-grid. However, affordability emerged as a significant concern for households with larger families, low or poor incomes, or higher energy demands. As Brown et al. [50] indicated, low-income households often feel financial strain when they are faced with making hard decisions between paying for energy and other critical needs such as food. Similarly, Ye and Koch [51] emphasize that households experiencing extreme energy poverty are often those living in income poverty, further reinforcing the link between energy affordability and economic vulnerability.

Nevertheless, despite a few households struggling with its affordability, the majority of the community perceives the mini-grid as more affordable than traditional energy sources such as paraffin and LPG. This perception has led to widespread acceptance of the mini-grid as a viable energy solution. As Zebra et al. [7] emphasize, the value of mini-grid systems lies in their "user-perceived value," which reflects the community's satisfaction with the system's performance and benefits. This perception is inherently linked to Tsoeu-Ntokoane et al.'s [17] assertion that social trust is a key factor in fostering community involvement. Social trust not only strengthens user confidence in the system but also enhances the perceived value by reinforcing the belief that the project is reliable, equitable, and beneficial. Together, user-perceived value and social trust form a feedback loop that underpins the sustainability and success of mini-grid energy systems, as they directly influence community acceptance.

6. Conclusion

This study sought to assess the impact of the hybrid mini-grid on the Upper Blinkwater community, particularly with respect to its effects on energy poverty alleviation and overall socioeconomic improvements. The results show that the mini-grid has been a catalyst for substantial socioeconomic changes and tremendous transformation in the community's energy landscape. Electrification has also gone beyond energy expenditure reduction with the modernization of life in fundamental ways, by improving access to energy, affordability, and quality of life. It has provided reliable lighting and powered modern appliances, including fridges, televisions, and washing machines. The technologies have made life easier, more efficient, and more convenient compared to the community's reliance on wood, paraffin, and other traditional energy sources. The mini-grid, in addition to these services, has facilitated wealth diversification with income-generating activities, including those led by women, demonstrating the effects of the mini-grid on economic empowerment. Hence, the mini-grid had been widely accepted by most households in the community as dependable and contributing to an improved quality of life.

Therefore, this study cannot emphasize enough the important role decentralized energy solutions like hybrid mini-grids can play in overcoming the specific challenges experienced in rural, off-grid locations. So to maximize the benefits of such projects;

- Governments should take a lead role by issuing policies to encourage the expansion of mini-grid projects in underserved rural areas, directing public-private partnerships to sustain these systems with ongoing maintenance and innovation.

- Gender responsive policies: Women, in particular, are beneficiaries of electrification that allows them with time-saving appliances and enhanced employment opportunities. Therefore, gender-sensitive policies should address ways to enhance women's access to energy and help them to engage in energy-related activities.

- Finally, improve community engagement; more community engagement in planning, operating, and sustaining mini-grids can lead to ownership, ensuring the relevance of projects to the beneficiaries, and making it sustainable over time.

Moreover, future research needs to focus on the long-term profitability of hybrid mini-grids and their ability to deliver reliable energy services with affordable tariffs without depending heavily on external funding. Comparative studies between different mini-grid technologies and implementation models could further this understanding. Another area worthy of exploration is the impact of community-based management and local leadership on the sustainability of these systems.

In summary, the Upper Blinkwater hybrid mini-grid project has provided transformative access to energy services, reduced energy expenditure, enabled diversification of economic activity, facilitated household growth and could serve as a promising model with transferable lessons for sustainable rural development. In this study, the focus is on the energy poverty gap, so this project illustrates how decentralized energy solutions can propel socioeconomic development while elevating the living conditions in rural communities.

Acknowledgements

The authors wish to extend their appreciation to the Eskom Tertiary Education Support Programme (TESP), the Renewable Energy Research Niche Area in the Department of Research and Innovation (DRI), the Council for Scientific and Industrial Research (CSIR), Dr. Shambira, Prof. Makaka, and the Raymond Mhlaba Municipality for their support. The authors acknowledge their sole responsibility for the content of this work, which does not necessarily reflect the official views of the aforementioned organizations and individuals.

Conflict of interest

The authors declare no conflict of interest.

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Chapter 10

Renewable Energy and Smart Technologies Integration for Adaptive and Sustainable Architecture

Shah Aarif Ul Islam and Edson Leroy Meyer

Abstract

This chapter explores how renewable energy systems and available smart technologies have been integrated into modern architecture in an attempt to increase sustainability, energy efficiency, and adaptability. In the past 10 years, global energy demand has been on the rise, and with it, the environmental concerns, resulting in the need for buildings to move toward self-sustaining buildings powered by renewable energy sources, including solar, wind, geothermal, and bioenergy. At the same time, smart technologies, such as IoT-enabled sensors, AI-driven automation, and sophisticated energy management systems help save energy use, reduce operations costs, and increase occupant comfort. This chapter examines such innovations in partnership to reduce environmental impact and maximize efficiency through their working in conjunction to create intelligent, self-regulating structures. Best practices are concerned about integrating renewable energy in architectural design, strategies about integrating smart building systems, and economic and policy implications of sustainable construction. Furthermore, topics including AI-optimized energy management, smart grids, and the next-generation materials have been introduced and the effect it could have on the built environment is discussed. Yet there are challenges in big initial investment and regulatory barriers as well as continuous technological advancements and supportive policies that pave the way for ever more viable sustainable buildings. This chapter presents a complete review of current developments, challenges, and prospects in the integration of renewable energy and smart technologies, befitting to architects, engineers, and politicians in architectural make toward sustainable architecture.

Keywords: renewable energy integration, smart building technologies, net-zero energy buildings (NZEBs) energy efficiency, sustainable building design, artificial intelligence in architecture

1. Introduction

In recent times, renewable energy systems integrated with smart technologies have become a way of transforming contemporary architecture toward sustainable development being energy-efficient, and adaptable to the users. Now, with the world looking for ways to cut down our carbon footprint and lessen the effects of climate change, the construction industry is a heavy contributor to the development of creative ideas *via* sustainable energy sources and intelligent automation. This chapter looks at how these technologies would discreetly intertwine and become revolutionary for the built environment.

1.1 Renewable energy and smart technologies in architecture

1.1.1 Overview of the need for sustainable architecture

A large amount of global energy and greenhouse gas emissions are accounted for by buildings. Currently used traditional architectural practices severely depend on fossil fuels further result in environmental degradation [1, 2]. With the increasing climate change and resource depletion emergency there is now an increasing need for architectural designs that lessen on ecological impact in the preservation of the environment while boosting the efficiency of the use of energy [3]. Retaining sustainable buildings are those, that are equipped with renewable energy sources such as solar, wind, and geothermal energy to minimize dependency on conventional power grids and strengthen resilience in case of an energy crisis. Furthermore, there is an increasing number of people living in urban areas and the heightened demand for energy should prompt architectural solutions that take into consideration comfort, functionality, and sustainability. Green building certifications like Leadership in Energy and Environmental Design (LEED) and Building Research Establishment Environmental Assessment Method (BREEAM) are being actively pushed by governments as well as by industry leaders for environmental threatening construction practices [4].

1.1.2 Defining renewable energy integration and smart technologies

Renewable energy integration refers to the incorporation of sustainable power sources into the design and operation of buildings [5]. It encompasses on-site generation from photovoltaic (PV) panels, wind turbines, geothermal heating as well as storage systems. At the same time, integrating renewable energy allows buildings to achieve a higher level of energy independence, lower costs of operation and lead to a lower carbon future [6]. On the other hand, smart technologies take digital innovations like the Internet of Things (IoT), artificial intelligence (AI), and advanced automation to leverage building performance. Real-time monitoring, predictive maintenance, and adaptive energy management are enabled by these technologies to make buildings operate efficiently or more efficiently when variables such as environment change. Both renewable energy and smart technologies allow for the synergic development of smart, self-sustainable structures, aligned to the current sustainability objectives [7].

1.2 Smart technologies for adaptive building systems

1.2.1 Overview of smart building technologies

Digital and automated systems in smart building technologies make better architectural structures, more efficient as well as more sustainable. The building technologies that integrate IoT-enabled sensors, artificial intelligence-powered automation, and cloud-based energy management integrated systems will optimize the building operation. Intelligent buildings are a collection of interlinked networks that can monitor, control heating, ventilation, air conditioning (HVAC), lighting, security, and energy use within a building [8]. Building Management Systems (BMS) implementation enables real-time monitoring of consumption patterns with actionable information on waste reduction and the optimization of system efficiency [9]. These are in line with global sustainability goals whereby, the buildings work at peak efficiency with minimal environmental impact.

1.2.2 Role of sensors, data analytics, and automation in adaptive architecture

The pillar of adaptive architecture lies in the integration of sensors, data analytics, and automation.

Sensors: Occupancy, temperature, humidity, air quality, and energy usage tracking capabilities are all tracked by sensors in smart buildings [10]. They are real-time sensors and thus can be used to automatically keep the indoor conditions optimal for comfort and efficiency.

Data analytics: Large volumes of data are collected from sensors that use AI-powered analytics. Such insights allow us to forecast the maintenance requirements, identify inefficiencies, and save energy spending by decreasing energy consumption. Further predictive analytics enables facility managers to point problems ahead of time before they occur and prolong the life of the building while lowering operational cost [11].

Automation: Automated building systems are highly responsive to the real-time data. For instance, smart HVAC systems will regulate temperature on how occupied it is, while the adaptive lighting systems will adapt brightness according to available natural daylight [10]. This way, in essence, adds to user experience as well as vastly reduces energy consumption.

1.2.3 Benefits and challenges of smart technologies in buildings

Benefits that can be derived through the integration of smart technologies into the built environment include improvements in energy efficiency, reduction in cost of operation, and improvement of overall user comfort [2]. Such technologies can help buildings to use energy optimally at any time. Real-time functions of smart heating, ventilation, and air conditioning (HVAC) and adaptive lighting lead to automated energy consumption systems such as from real-time occupancy, and environmental factors. Such a reduction in energy waste makes buildings more sustainable and significantly reduces electricity bills. Likewise, artificial intelligence (AI) and machine learning-supported predictive maintenance ensure that building systems work at their peak. Smart technologies help in analyzing historical data to prevent malfunctions from occurring and minimize downtime as well as repair costs [12]. The other main advantage of smart buildings is the improvement of occupant comfort and productivity. Smart technologies feature intelligent climate control, air quality monitoring and adaptive lighting, which together constitute an optimal indoor environment based on user preferences. Smart thermostats can learn occupants' schedules, and automatically adjust temperature settings to keep people comfortable, and saving unnecessary energy [13]. Moreover, the building security and access control are further enhanced by the integration of AI-driven security systems like facial recognition, motion sensors, and automatic locks, making the vicinity safer for occupants.

However, smart technologies in buildings also have several challenges. The high initial investment needed makes it the greatest barrier to widespread adoption. It is costly to install IoT sensors, AI-driven management systems, or automation tools and thus may dissuade property developers and homeowners from going in for these. Also, smart devices widespread use growth is raising privacy and security. Considering that smart buildings are based on networks intertwined with each other and embedded in clouds, they are exposed to hacking, and other cyber threats such as unauthorized data breaches [14]. It is important to ensure that the system has robust cybersecurity protocols to save the data of the user and maintain the integrity of the system. The complexity of the integration problem is because smart buildings rely on many technologies and platforms that ought to be integrated. This situation can result in conflicts in relation to different smart devices and management systems and require skilled professionals to set up, install and maintain those integrated solutions. In addition, smart building technologies rely on digital infrastructure, which can impact them because of the failures of the systems, software glitches and power outages [15]. To ensure there's no continuity of service, smart buildings should also have redundancy and backup mechanisms. However, this does not eliminate the challenge of supporting diverse and growing building tenants and communities while developing affordable housing; continuous advancements in AI, IoT, and automation are offering more robust and feasible smart building services.

1.2.4 Scope and objectives of the chapter

In this chapter, we examine the connection between energy and smart technologies in the field of modern architecture focusing on how they can build adaptive, energy-efficient and sustainable buildings. Together with those advancements, architects, engineers, and urban planners can better build performance, decrease environmental impact as well as give better comfort to occupants with the integration of these advancement. A major emphasis is placed on the assessment of the use of renewable energy in architecture, including solar, wind, and geothermal solutions for residential, commercial, and industrial applications. These technologies will then be evaluated in terms of their feasibility and cost-effectiveness for stakeholders to be able to use them effectively. The chapter also explores smart technologies such as IoT-enabled sensors, AI-enabled automation, etc., along with intelligent energy management systems. These innovations allow for self-regulating buildings with predictive maintenance with reduced operational costs and increased efficiency. The case studies from the real-world will feature the successful implementation, and the discussions of challenges and mitigation strategies will present some practical experience. It also presents best practices for designing with renewable and smart systems and recommends changes to industry practices and policy for policymakers and industry professionals. It finally discusses emerging trends like AI and machine learning as well as smart grids, to define the future of intelligent, sustainable buildings. This chapter also provides a contribution to advancing an ecofriendly resilient built environment in line with global energy and climate policies by taking into consideration these aspects.

2. The role of renewable energy in sustainable building design

The sustainability transition in architecture demands renewable energy integration because it allows the reduction of environmental impact and improves energy

DOI: http://dx.doi.org/10.5772/intechopen.1009931

efficiency standards. Buildings consume a substantial amount of global energy, so the incorporation of renewable energy systems becomes vital both for fuel reduction and sustainability achievements [15]. This section reviews different renewable power systems in architectural projects alongside their deployment in construction alongside their execution difficulties.

2.1 Types of renewable energy systems for buildings

Multiple renewable energy sources integrated into buildings create opportunities to produce uncontaminated power while enhancing the energy stability of structures. Several renewable energy systems have gained the most widespread acceptance among architects which include:

Solar energy: Solar power consists of photovoltaic (PV) panels and solar thermal systems that turn sun rays into electric power and hot water delivery thus making solar energy fundamental and simple to scale for renewable applications. Sustainable architecture implements rooftop solar panels together with Building-Integrated Photovoltaics (BIPV) technology and solar shading systems (**Figure 1**) [17].

Wind energy: The implementation of small-scale wind turbines enables the production of electricity directly at a building site. Wind energy works better at elevated positions and open spaces, but new urban wind power technologies are improving wind energy potential in metropolitan areas.

Geothermal energy: Geothermal heat pumps extract heat from belowground to heat and cool buildings through a process which yields highly efficient and carbon-free energy. Geothermal systems deliver their best advantages in regions characterized by major geothermal heat production.

Biomass and bioenergy: Biomass boilers together with biofuel-based heating systems transform organic waste into energy which serves as an alternate heating fuel source [18].

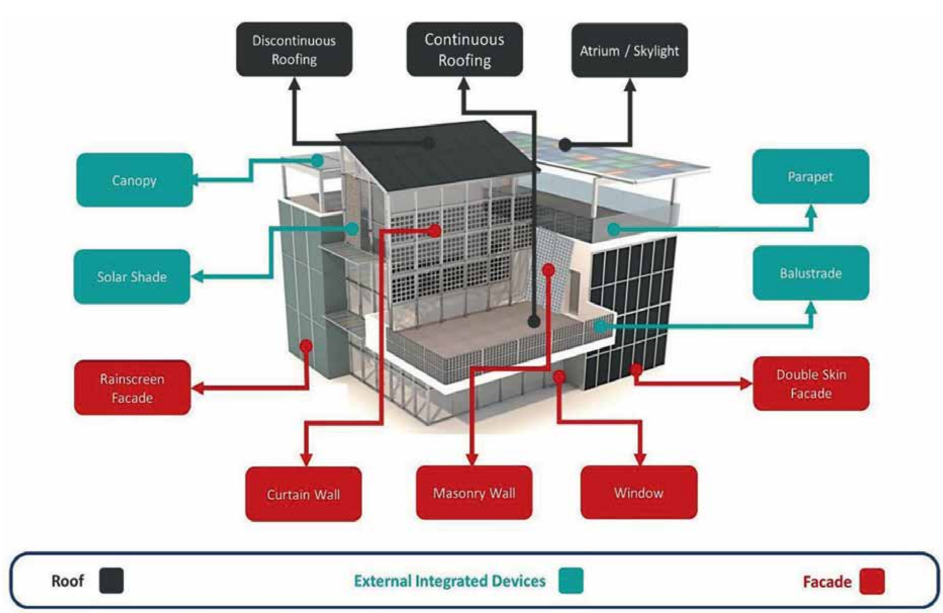

Figure 1.
Solar integration in a building, BIPV, and solar shading. Reproduced from Ref. [16] under CC BY license.

Hydroelectric and rainwater energy: The combination of hydroelectric along with Rainwater Energy systems that use energy-producing turbines enables localized renewable energy generation near water sources.

2.2 On-site and off-site renewable energy solutions

The integration of renewable energy systems in buildings occurs through on-site and off-site solutions which provide separate benefits:

On-site solutions: Rooftop solar panels together with geothermal heat pumps enable buildings to produce their electricity and heat directly at the site. The combination of these systems offers energy independence in addition to lower utility costs and improved resilience in case of power outages. The implementation of net-metering policies enables buildings to boost economic performance by providing excess power back to the electrical grid [19].

Off-site solutions: The procurement of renewable energy through solar farms and wind farms located at distances from buildings constitutes off-site renewable energy solutions. The method proves perfect for buildings that lack sufficient space and those located where there are not enough solar or wind resources. Power Purchase Agreements (PPAs) together with green energy certificates enable organizations to fund renewable energy projects even when they do not have on-site facilities.

2.3 Benefits and challenges of renewable energy in buildings

2.3.1 Benefits

The integration of renewable energy systems holds multiple benefits for building designs:

Environmental sustainability: Reduces greenhouse gas emissions and dependence on fossil fuels.

Resilience and energy security: Provides energy autonomy and mitigates the impact of grid failures.

Energy cost savings: Lowers operational expenses by utilizing free and abundant energy sources.

Enhanced property value: Buildings that implement renewable energy systems become more desirable to potential buyers and tenants because they seek properties with energy-efficient features.

Regulatory compliance: Buildings can achieve compliance with LEED and BREEAM sustainability standards thanks to regulatory compliance.

2.3.2 Challenges

Despite its benefits, renewable energy integration presents several challenges:

High initial investment: The development of renewable energy infrastructure requires significant funds before operations start.

Intermittency issues: The inconsistent nature of solar and wind power requires solutions for energy storage because the weather drives their availability.

Space limitations: The implementation of certain renewable systems needs considerable rooftop space or land area which could be beyond reach for various buildings.

Integration complexity: Combining multiple renewable energy sources with existing grid infrastructure can be technically challenging.

Regulatory and financial barriers: Inconsistent policies, permitting issues, and financing constraints may hinder widespread adoption.

By overcoming these challenges through technological advancements, policy support, and strategic planning, renewable energy can play a central role in shaping the future of sustainable architecture.

3. Synergies between renewable energy systems and smart technologies

The integration of renewable energy systems with smart technologies is revolutionizing sustainable architecture by enabling efficient energy management, optimizing consumption patterns, and enhancing overall building performance. Smart technologies enhance the usability and effectiveness of renewable energy by ensuring real-time monitoring, automated control, and predictive analytics [19]. The section discusses how smart grids and energy storage capabilities together with advanced energy management systems create optimal relationships between renewable power sources and building smart systems.

3.1 Smart grids and energy storage for sustainable buildings

Energy-efficient buildings require smart grids along with storage solutions to achieve maximum integration success of renewable energy systems.

Smart grids: Smart grids represent advanced electricity systems that employ digital communication networks combined with automation to maximize the consumption and distribution of power [20]. Smart building infrastructure that links renewable energy sources to smart grids allows effective electricity demand control while balancing peaks through power return capability to the electricity network. Building energy utilization can be managed through demand-response protocols that function according to supply-demand patterns in the electric grid system thereby maximizing power efficiency.

Energy storage systems: Lithium-ion batteries and flow batteries, along with thermal storage systems, act as energy storage solutions to sustain stable energy supplies because renewable energy from sources such as solar and wind has intermittent qualities [21]. Building facilities equipped with battery storage systems can accumulate solar power during the daytime for nighttime or emergency power usage, thereby increasing their energy independence and resilience. Artificial intelligence analytics within advanced energy storage management systems optimize battery usage while enhancing operational performance and improving system lifespan effectiveness.

3.2 Integration of smart energy management systems (EMS)

Smart energy management systems through the integration of IoT together with AI and automated solutions optimize the consumption of renewable energy power in buildings. The systems complete multiple essential operational duties:

Real-time monitoring: The Internet of Things uses sensors to track building performance by continuously monitoring solar generation and energy usage as well as temperature data occupancy levels and multiple other parameters.

Automated energy optimization: AI operates EMS to modify heating and cooling along with lighting uses autonomously based on building occupancy patterns and energy capacity data hence minimizing energy waste.

Predictive analytics and demand forecasting: Machine learning algorithms in predictive analytics and demand forecasting models evaluate past energy analytics to anticipate upcoming consumption patterns for proactive energy control [22].

Grid interaction and load balancing: The EMS system enables buildings to communicate efficiently to the smart grid through load balancing and by responding to live electricity prices along with grid stability requirements.

Solar and wind energy integration through EMS systems enables buildings to obtain major energy savings and minimum carbon emissions together with improved operational effect.

3.3 Examples of smart technologies enhancing renewable energy utilization

Today smart technologies are integrating with the renewable energy systems to transform the way that building creates, store, and control energy. Today, modern structures are far more efficient, self-sustaining, and green based on advanced digital solutions like artificial intelligence (AI), Internet of Things (IoT), automated energy management, or automated energy management (AMM), and so forth [23]. The effectiveness of this integration in the developed energy ecosystem is shown through several real-world applications.

3.3.1 Net-zero energy buildings (NZEBs)

Net-zero energy buildings (NZEBs) are built to produce as much energy as they use, therefore they are not reliant on external power [24]. Renewable energy technologies such as rooftop solar panels, wind turbines, and geothermal heat pumps as well as AI-driven energy management systems are included in these buildings. Lithium-ion or solid-state batteries store excess energy that can be used when generation is low. Further, energy consumption is also optimized by AI algorithms, which predict usage patterns that can adjust HVAC operations and manage lighting efficiency. NZEBs play a major role in carbon neutrality as well as long-term energy cost saving (**Figure 2**).

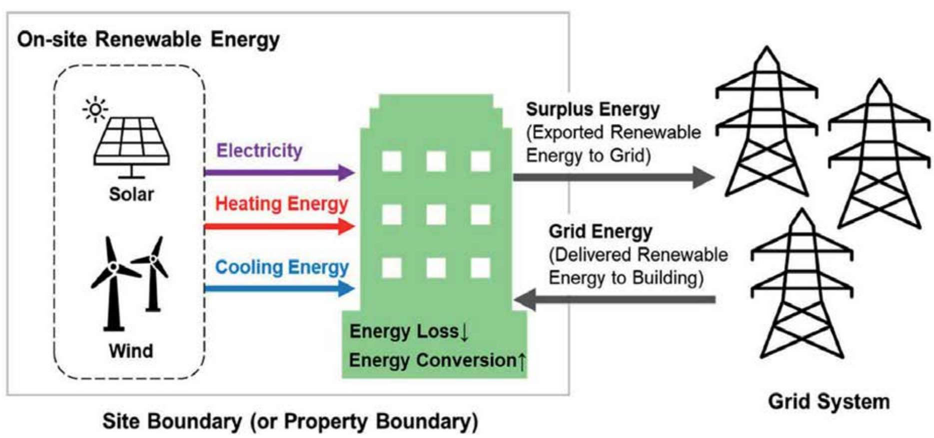

Figure 2.
Configuration diagram and energy flow of a net-zero energy building, Reproduced from Ref. [25] under CC BY license.

3.3.2 Intelligent microgrids

Local energy generation, distribution, and local storage in smart microgrids are possible on a residential and commercial scale. The smart grid technology allows decentralized grids to plug in renewable sources of power such as solar and wind power [26]. Owing to its throughput requirement, microgrid controllers' supply and demand life cycle scheduling is optimized with the help of AI. Furthermore, the decentralized peer-to-peer (P2P) energy trading platforms based on blockchain also offer to share surplus energy among the buildings and lower the reliance on the centralized power grids, and enhance energy security [27].

3.3.3 AI-optimized HVAC systems

A large portion of a building's energy is used for heating, ventilation, and air conditioning (HVAC). Predicative analytics, weather forecasting, and building occupancy data are used by AI-powered HVAC systems to improve the efficiency of the systems controlling temperatures. Real-time environmental conditions are used in smart HVAC systems to control cooling and heating functions to reduce energy waste and keep the indoor space comfortable at the same time [10]. In addition, AI-driven maintenance alerts and their precise identification of system inefficiencies of the system before failures prevent operational costs and contribute toward the sustainability of the system.

3.3.4 Smart home energy systems

The use of renewable energy has greatly increased in residential buildings with IoT-based smart home technologies. The features of the smart thermostats are learning user preferences and automatically adjusting heating or cooling to save energy [13]. In general, adaptive lighting systems using motion sensors, and daylight-responsive dimming, lower electricity consumption using natural light when available. The shading systems that use automation include smart blinds and electrochromic glass, regulating indoor temperature by being controlled automatically based on the intensity of sunlight to decrease HVAC loads [28]. These technologies are solar panels integrated with battery storage and are integrated together to maximize energy efficiency and reduce electricity demand.

Through these smart technologies, buildings can move toward more sustainable, resilient energy ecosystems and help create a smarter, greener future.

4. Design considerations for architects and engineers

Placing a balance between the creation of the sustainable, functional, and esthetic elements of buildings, building design integrates smart technologies as well as the renewable energy systems. Balancing energy efficiency with architectural structure and integrity, user comfort and technological feasibility poses a challenge for architects and engineers. This section covers best practices on renewable energy, smart technologies implementation strategies and challenges of building sustainability with respect to architectural design.

4.1 Best practices for integrating renewable energy in architectural design

Architects must also think about site-specific factors, energy demand, and available technologies to successfully integrate a renewable energy system in a building. Key best practices include:

Site analysis and orientation: Orienting the structures to maximize exposure to the sun and positioning photovoltaic (PV) panels strategically reduces energy consumption. Optimal sunlight exposure is received by south facing rooftops (in the Northern Hemisphere) or facades (**Figure 3**) [29].

Building-Integrated Photovoltaics (BIPV): Embedding solar panels into the structure of the building are known as Building-Integrated Photovoltaics (BIPV) [30]: It helps to bring in the renewable energy in harmony with the architectural design.

Passive Solar Design: Thermal mass, shading devices, and high-performance glazing incorporated along with renewable energy usage reduce the need for artificial heating and cooling, Passive Solar Design.

Hybrid Renewable Systems: Combining several renewable sources, especially solar, wind, and geothermal, makes it possible to ensure a constant energy supply and minimize the dependence on a single energy source called Hybrid Renewable System.

Energy storage and grid connectivity: Through the design of buildings with battery storage and smart grid connectivity, buildings are made more energy resilient and help in optimal distribution of energy.

4.2 Strategies for incorporating smart technologies in building systems

Integrating smart technologies must be done in such a manner to achieve optimal building performance and long-term adaptability. Key strategies include:

IoT-enabled monitoring and control: Monitoring and controlling the use of energy, occupancy, temperature, and air quality through deploying sensors.

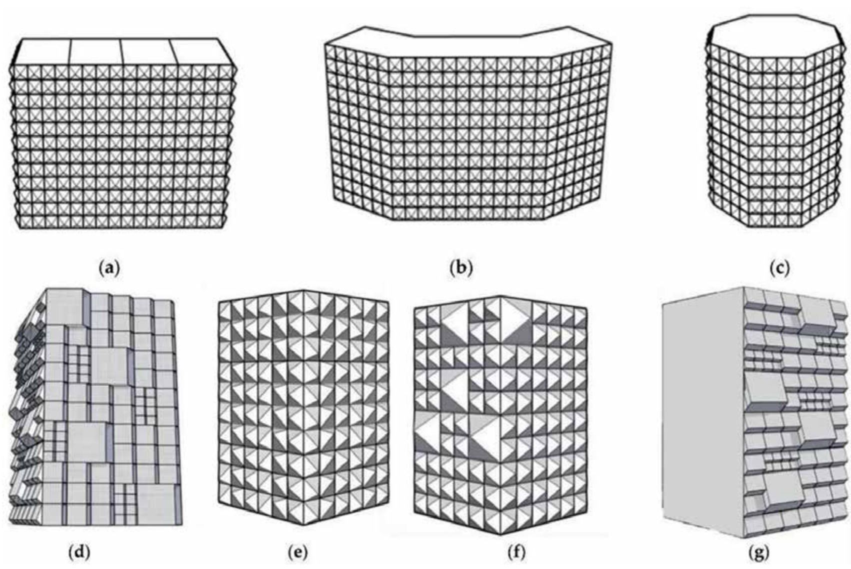

Figure 3.
Architectural planning for enhanced solar efficiency, (a–c) arrangement of structures, (d–g) buildings exteriors (facades), reproduced from Ref. [16] under CC BY license.

Automated and adaptive systems: Smart shading, dynamic glass, and responsive lighting systems reduce energy consumption by adjusting to environmental conditions [31].

Interoperability and scalability: The use of standardized protocols means that systems designed in such a way are easy to integrate other smart devices and future technology upgrades.

AI and machine learning optimization: AI and machine learning are used in energy management systems with AI predicted to improve energy efficiency through demand prediction, HVAC settings, and improved lighting.

Cybersecurity measures: As smart buildings rely on interconnected digital systems, robust cybersecurity protocols are essential to protect data privacy and prevent system vulnerabilities.

4.3 Balancing aesthetics, functionality, and sustainability

Sustainable building design must be designed architecturally, and esthetically with a due balance for functionality of the building and energy efficiency. Building design integrity is a challenge for incorporating renewable energy and smart technologies without impacting the growth of the leasable building area. Key considerations include:

Material selection: Material selection is a key point of sustainable design. Rather than using materials like recycled steel, bamboo, low emission glass while utilizing ecofriendly and energy-efficient materials also reduces environmental impact [32]. Preserving its architectural integrity, these materials support the sustainability of a structure.

Minimalist and modular design: One of the key things one must think about when designing a front-end responsive website or desktop web application is a minimalist and modular design. Modular and prefabricated components are easier to assemble and therefore have less waste and little energy is used. Renewable energy solutions, including solar panels, green roofs, and so on are easily accommodated within such designs while continuing to maintain collective esthetic harmony.

Human-centered design: Human-centered design is important as it makes sure that technology improves user experience and not the other way around. Intuitive and accessible smart lighting, ventilation and energy management systems should be used to promote comfort and well-being of the occupants.

Regulatory compliance: Regulatory compliance also adds an important function in the sustainable building design [32]. To ensure the buildings accommodate high sustainability standards and mold green certification bodies like Leadership in Energy and Environmental Design (LEED) and Building Research Establishment Environmental Assessment Method (BREEAM), follow green certification standards such as how to reduce energy, water usage, and indoor air quality.

Architects can thus integrate these principles in the construction of technologically advanced, and environmentally responsible buildings, as well as esthetically attractive ones. Thoughtful execution of sustainable architecture harmonizes future modern innovations with ecological responsibility, establishing a precedent for future developments.

5. Economic and policy implications of renewable and smart technology integration

Economic and policy considerations of the integration of renewable energy and smart technology in architecture are significant. These technologies are long-term cost saving, energy-efficient, and more sustainable but come with high investment and regulatory issues in the early stage. The feasibility of the approach, regulatory frameworks, and opportunities for policy inducement of the adoption of sustainable building solutions are considered in this section.

5.1 Cost-benefit analysis of renewable energy and smart technologies in construction

Different factors such as initial capital investment, operational savings, and long-term financial returns make the integration of renewable energy and smart technology economically feasible.

5.1.1 Initial investment costs

Installed costs for renewable energy systems or smart technologies can be high in upfront. Large capital is needed for PV panels, battery storage, geothermal systems and wind turbines, as well as for smart building automation, AI energy management, and IoT sensors. Furthermore, these systems are specialized and integrating them adds labor and installation costs.

5.1.2 Operational savings and long-term benefits

High initial investments are required for smart and renewable energy-integrated buildings, but they provide large long-term savings. The key benefits include:

Energy cost reduction: Solar panels and wind turbines help to reduce the dependence on grid electricity. Smart energy management systems also enable consumption to be optimized, thus preventing waste.

Predictive maintenance savings: AI and IoT-based monitoring systems help them predict when the probable equipment failure is going to happen; hence, saving money on static maintenance expenses and saving time loss from the situation [33].

Increased property value: Green certified and smart-enabled buildings have a higher resale and rental value primarily because they are energy-efficient and thus sustainable.

Incentives and tax benefits: Many governments do certain financial incentives like tax credits, rebates or grants to promote renewable energy adoption and smart building technology.

Typically, a comparative cost-benefit analysis will show that such investments are initially high, however reduction in energy costs, operational expenses and maintenance makes these technologies cost effective over a building's life.

5.2 Policy and regulatory support for sustainable building initiatives

Government plays a crucial role in the promotion of the adoption of renewable energy and smart technologies of buildings. Regulatory frameworks that work are promising to investment, help with compliance to standards of sustainability, and permitting integration into the existing structure.

5.2.1 Global and regional policies

Sustainable buildings are supported by various international and national policies:

Renewable energy standards and mandates: Countries have set goals of renewable energy that are a percentage of sustainable energy. In fact, the European Union's Green Deal states that its buildings must be carbon-neutral by 2050 [34].

Building energy codes and certifications: Regulations like Leadership in Energy and Environmental Design (LEED), Building Research Establishment Environmental Assessment Method (BREEAM) or Passive House standards define minimum requirements or which building can withstand the framework elements, for example a minimum system of energy efficiency and intelligent building integration [35].

Net-zero energy policies: In some areas, new buildings need to be net zero energy, which means that they generate as much energy as they consume. Innovations for renewable and smart energy systems are stimulated by policies that drive net zero construction.

Incentives for green construction: Grants, Low-Interest Loans, and Tax Incentives assist in the inducement of developers to add renewable energy and smart technology in his projects.

5.2.2 Barriers to policy implementation

Despite policy support, several challenges prevent large-scale adoption of sustainable building practices. Regulations vary from one region to another, and thus building codes also vary, which becomes difficult to comply to for developers due to *Lack of standardization*. Furthermore, small firms do not participate, for whatever reasons, because of the *high compliance costs* in meeting sustainability certification, discouraging widespread adoption. Additionally, there is another factor, *slow policy adoption*, which further exacerbates the issue, as bureaucratic delays and weak enforcement of the existing regulations put a dent in the effectiveness of the regulations in question. Daunting barriers to green construction have arisen, to be overcome by these governments should be streamlined framework of regulatory, create unanimity from sustainability standards from all the regions of the country, and incite stronger financial incentives, including tax credits, subsidies, or low-interest loans for green construction. Addressing these challenges allows policymakers to speed up the transition into a greener built environment.

5.3 Challenges and opportunities for adoption in different regions

Renewable energy and smart technologies are adopted to different extents in different regions, primarily by way of differences in economic development, energy infrastructure, and policy frameworks.

5.3.1 Developed regions

In industrialized nations, with specific examples of the United States, the European Union, and Japan, a need for renewable energy integration is induced by stringent environmental regulations, financial incentives, and advanced infrastructure. Challenges include:

Aging grid infrastructure: The grid infrastructure that is currently in place to deliver electricity is aging and therefore costly to upgrade to be able to deliver the electricity that decentralized renewable energy will require.

High initial costs: Despite incentives, upfront investment remains a barrier to widespread adoption.

Cybersecurity risks: Smart buildings increase their reliance on digital infrastructure that can be used as a gateway for cyber threats [36].

5.3.2 Developing regions

Renewable energy is a chance for emerging economies to solve the problem of energy shortages and reduce the dependence on fossil fuels. Nevertheless, adoption has disadvantages, including:

Limited financial resources: High installation cost slows down the rate of adoption.

Insufficient policy support: A weak regulatory environment does not motivate investment into renewable and smart technologies.

Energy access issues: There are some regions that have minimal basic electricity infrastructure, and embracing such desired advanced technologies should arguably be preceded by the development of basic infrastructure.

Despite these challenges, the progress of these developing countries has not been smooth, but they still have an opportunity to skip the traditional path of energy infrastructure by jumping into decentralized renewable energy measures. For instance, off-grid solar and microgrid systems supply electricity to remote communities reducing the environmental impact they have traditionally borne.

5.3.3 Opportunities for global adoption

Public-Private Partnerships (PPPs): Public-Private Partnerships (PPPs) can help to speed up the uptake of renewable and smart building technology through collaborations of governments, private investors, and technology providers.

Technological innovations: Advances in AI, IoT, and energy storage continue to lower costs, making sustainable solutions more accessible.

International climate agreements: Global frameworks such as the Paris Agreement may be guiding international climate agreements to encourage countries to adopt policies that encourage renewable energy integration in buildings.

The role of renewable energy and smart technology integration in the economic and policy dimensions to create future sustainable architecture is very crucial. While these solutions are expensive on initial investment and in terms of regulatory complexities in the long run the benefits with respect to the energy cost savings, increased property value, and environmental sustainability make the solutions viable. As the smart and renewable energy-integrated buildings build up policy support, financial incentives, and technological progress, the country will see the build up of adaption of smart and renewable energy-integrated buildings, which will help the world have a sustainable built environment.

6. Future trends in adaptive and sustainable architecture

As more and more renewable energy and smart technologies converge into shaping the future of architecture, so does the need for adaptive, sustainability of their own, and highly efficient buildings. The consumption of energy by buildings today—and their management of it—is changing because of innovations in artificial intelligence, energy storage, and integrated building systems. This section focuses on some of the trends that are going to make sustainable architecture evolve and they include advanced renewable technologies, AI-driven building management, and how smart cities will play its role in the built environment.

DOI: http://dx.doi.org/10.5772/intechopen.1009931

6.1 Emerging renewable technologies and smart systems

Solar and wind energy still dictates the scene as the most used renewable energy sources, but further advancements are improving efficiency and increasing applications of the two in architecture.

6.1.1 Next-generation solar technologies

Perovskite solar cells: These high-efficiency and cheap solar cells are what could replace silicon-based panels to revolutionize photovoltaic in the future with better flexibility and higher energy conversion [37].

Building-Integrated Photovoltaics (*BIPV*): Transparent solar windows, solar facades and flexible PV films facilitate seamless blending of solar power with building materials to generate energy as well as build good looks.

Solar thermal systems: Enhanced solar heating and cooling technologies (hybrid photovoltaic-thermal [PVT] systems) on the other hand are the most advanced solar thermal systems that together provide electricity by generating electricity and collecting heat.

6.1.2 Innovations in energy storage

Solid-state batteries: Solid-state batteries provide higher energy density and longer lifespans than lithium-ion batteries and will make energy storage more efficient for the smart buildings of the future [38].

Hydrogen storage: Green Hydrogen is considered a possible viable energy carrier since it is used to store excess renewable energy for later use.

Gravity and kinetic storage: Other energy storage in the form of novel gravity-based systems, or kinetic flywheels are better solutions for their use of finite resources, versus battery storage systems [39].

6.1.3 Advanced wind and geothermal systems

Vertical-axis wind turbines (*VAWTs*): As urban environments continue to grow, affordable, low-noise wind turbines are becoming more viable for urban populations in increasing numbers, providing wind energy in clustered populations.

Geothermal-Integrated Smart HVAC: AI-optimized geothermal heating and cooling systems for building use, Geothermal-Integrated Smart HVAC.

6.2 The role of artificial intelligence and machine learning in adaptive architecture

Building management through real-time consumption of energy flags will lead to revolutionizing building management through automation, predictive analytics, and optimization of energy consumption along with AI and machine learning. Key applications include:

Self-learning building management systems (BMS): Artificial intelligence (AI) driven systems to monitor the occupancy patterns, weather conditions, and the energy demand of the building to provide the automated lighting, HVAC and the storage of energy to save costs.

Predictive maintenance: Machine learning algorithms predict equipment failures and reduce maintenance costs with Predictive Maintenance: Anomalies in building infrastructure are predicted before the failure of equipment happens [40].

Energy demand forecasting: Prediction of fluctuations in the energy demand: AI boosts the interaction of the grid by predicting fluctuations in the energy demand and adjusting the building energy usage optimally according to the consumption of renewable energy [41].

AI-powered smart grids: Adaptive energy distribution network through AI: Integrated distributed energy sources for supply & demand balancing and strain reduction on the grid.

6.3 Potential for integrated building systems in smart cities

Intelligent building systems that are integrated seamlessly with the urban infrastructure enhance the more sustainable and efficient environment. This transformation is supplied by *interconnected smart building ecosystems* that will allow buildings to interact dynamically with their surroundings. Presenting structures with renewable energy systems and smart meters with the opportunity to trade in excess electricity with their neighboring structures *via peer-to-peer (P2P) energy* trading would allow them to decrease reliance on centralized grids. *Urban energy networks* will also connect residential and commercial buildings through microgrids to share their renewable resources and to increase urban resilience. Further, AI-powered *real-time environmental adaptation* will continue to optimize urban infrastructure through the monitoring and controlled energy distribution, controlled traffic patterns, as well as controlled water management to support sustainable city operations.

Construction, and the material that goes into it, will be transformed through advancements in *sustainable materials and 3D-printed buildings*. Autonomous *self-healing concrete* will perform self-repair of structural cracks in the structure increase the lifespan of the building and reduce maintenance costs. Furthermore, *carbon-negative construction materials*, including bio-based composites, hempcrete and graphene-enhanced cement will significantly reduce the carbon footprint of new buildings. *Smart 3D printed structures* driven by AI will revolutionize urban development through rapid and cheap construction from sustainable materials using the most efficient resource utilization. However, the smart cities of the future will continue to grow the sustainability of renewable energy, advanced energy storage, as well as AI-driven urban planning. Given the fact that these technologies are ongoing to evolve, architects, engineers, and policy makers must adopt tech that is cutting edge hence designing resilient, energy efficiency, human-centric built environments that are sustainable to a certain degree.

7. Conclusion

Renewable energy systems (RES) and smart technologies integration in architecture signifies a defining change as they lay the foundation for sustainable, adaptive, and energy-efficient buildings. In this article, we discussed solar, wind, geothermal, and other renewables along with smart building technology like IoT, AI-based automation, and energy management systems that help reduce carbon footprint, make occupants more comfortable and increase operational efficiency. In smart grids, buildings can use energy storage solutions, and predictive analytics and optimize energy consumption and waste minimization, as well as be more resilient against energy disruption. However, the significant initial costs, regulatory barriers, as well as integration complexities, pose challenges, but technological advancements, financial incentives, and supportive policies are also making their contribution to encouraging adoption. The architects and engineers must play a pivotal role in making the sustainable design principles to integrate and balance between esthetics as well as functionality to meet the global green building standards. Also, AI-powered building systems, next-generation solar and energy storage technologies, and interconnected smart city infrastructures will lead to a future where buildings will be not only wise in consuming energy, but also in building and working together with the fabrics of the city. At this moment, where we are headed with net zero and carbon-neutral construction, industry professionals, policymakers, and researchers need to come together to deliver scalable, cost effective, and resilient solutions that work. Innovations should be embraced in the built environment and enable it to play a key role in global sustainability efforts by making cities smarter, greener, and more adaptive.

Acknowledgements

The authors are thankful to PV Spoke National Science and Innovation Energy Research Programme and National Research Foundation (GUN: 137944 and 118947) and Govan Mbeki Research and Development Centre (GMRDC), South Africa, University of Fort Hare.

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Edited by Masa Noguchi

The pursuit of sustainable built environments has become a strategic global priority in addressing the complex interplay of social, economic, environmental, and human development challenges outlined in the United Nations Sustainable Development Goals (SDGs). Accelerating urbanization, climate risks, and widening inequality are placing unprecedented strain on cities and communities, demanding a fundamental shift in how we design, deliver, and manage the built environment. Sustainable built environments are central to achieving key Sustainable Development Goals (SDGs)—particularly SDG 11 (Sustainable Cities and Communities), SDG 3 (Good Health and Wellbeing), SDG 7 (Affordable and Clean Energy), and SDG 13 (Climate Action). Built infrastructure must minimize environmental impact, maximize energy efficiency, and enhance the quality of life while placing people at the center, ensuring inclusivity, resilience, and adaptability to future needs. A leading example of this approach is the Zero Energy Mass Custom Home (ZEMCH) initiative. ZEMCH promotes the delivery of affordable, high-performance housing that meets both individual and community needs. By combining mass customization with energy-efficient design and renewable energy technologies, ZEMCH homes aim to achieve net-zero energy consumption, reduce their carbon footprint, and enhance occupant wellbeing. Equity and accessibility must also be embedded in the built environment, ensuring that all individuals, regardless of income, age, or ability, can access safe, functional, and dignified spaces. Ultimately, sustainable development is not only about constructing greener buildings but also about shaping environments that foster social cohesion, environmental stewardship, and long-term wellbeing. Achieving this requires cross-sector collaboration, meaningful community engagement, and the integration of sustainability principles throughout the entire lifecycle of the built environment, transforming it into a catalyst for positive change for both people and society.

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Sustainable Development Series Editor

ISSN 2753-6580
ISBN 978-1-83634-522-0

Published in London, UK
© 2025 IntechOpen
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