Building retrofit solutions in the context of energy resilience and urban environment regeneration

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Abstract. This paper highlights the role of building retrofitting in developing energy-resilient communities as a part of sustainable urban regeneration. Different approaches and technologies are covered, with the role of improving the energy performance of existing buildings by utilizing, among others, innovative insulation materials or renewable sources for heat supply combined with advanced smart control systems. The case studies from different parts of the world illustrate that this techno-economically viable retrofitting approach can reduce around 40 % energy consumption and emissions, making buildings more sustainable. The analysis of the new economic and regulatory is connected with the government's incentives as well as public engagement in developing positive energy communities. This paper also documents an extensive evaluation of retrofit technologies and their application, demonstrating the critical contribution energy retrofits can make towards achieving enduring urban sustainability.

1 Introduction

The concept of an energy community revolves around creating environments where buildings generate the needed energy for operation. This approach not only aims at reducing energy consumption but also seeks to contribute surplus energy back to the grid or to the community. With the increasing need to combat climate change and transition towards sustainable energy systems, retrofitting existing buildings represents a very important goal for the near future. By upgrading older structures including the urban spaces with modern technologies and materials and renewable energy sources, we can significantly improve their energy efficiency, therefore leading to a decrease in the carbon footprint of the building sector [1].

Retrofitting is essential due to the significant energy consumption associated with buildings, which accounts for nearly 40% of global energy use [2]. Many buildings, particularly older ones, lack the necessary insulation, energy-efficient windows, and efficient heating and cooling systems. Therefore, improving these aspects through retrofitting is a key step toward achieving energy savings. This article aims to explore the various strategies and technologies employed in retrofitting buildings, the first step for implementing small energy communities.

In the following, several successful case studies, showcasing real-world applications and theoretical analysis of retrofitting technologies and strategies are presented. These examples illustrate the potential benefits, challenges, and lessons by researchers.

Borras et al. [3] state that energy communities significantly improve building self-sufficiency by moving from individual to collective self-consumption, especially with diverse demand profiles like residential and school buildings. In the case studied, self-sufficiency increased from 16% to 34%, with centralized battery storage boosting it by an additional 16%. However, this comes with reduced economic viability, highlighting the need to balance energy efficiency and financial considerations. While collective self-consumption without battery storage was economically feasible, introducing battery systems led to lower economic returns. This highlights the importance of public support and funding to enhance the economic viability of energy communities, particularly when incorporating storage solutions for long-term sustainability. In addition, the improved energy efficiency (e.g. improved indoor climate, reduced energy cost, improved property value, etc.) must be recognised, and the lifetime costs of buildings have to be considered rather than just focusing on initial investment costs.

The optimization of building energy systems and envelope retrofits demonstrate that a combination of both can significantly reduce greenhouse gas (GHG) emissions while minimizing costs, according to Wu et. Al [4]. Retrofitting building envelopes, particularly in older buildings, coupled with the installation of renewable energy systems like heat pumps and solar panels, can achieve up to 76% GHG reduction with only a 3% cost increase. This is particularly beneficial for energy communities aiming to enhance sustainability. However, the optimal strategies vary based on the size, and existing energy systems of buildings, and their level of maintenance.

When residential buildings are extensively retrofitted to meet Passive House requirements, the energy consumption can drop by 43% as Johari et al. demonstrated in [5]. This illustrates how deep energy upgrades have a major effect on energy efficiency. Furthermore, rooftop solar PV systems can participate to the energy efficiency goal, turning buildings into near-zero energy districts or, in less populated areas, even positive energy districts.

According to Aruta et. Al [6], upgrading residential buildings with energy-efficient technologies and integrating renewable energy sources can result in notable sustainability and energy savings. The highest performance metrics were attained when upgrading the envelope and buildings' system were replaced.

The Ali U. et al. study's findings [7] show how incorporating data-driven machine learning techniques can significantly improve the prediction of urban building energy performance, which is essential for retrofit planning. The accuracy of the suggested model was 91%. A synthetic dataset representing one million residential dwellings in Ireland was created by applying parametric simulations to four different architectural archetypes. The efficiency of retrofitting procedures was demonstrated by this large dataset, especially when examining energy use intensity for equipment, lighting, and heating systems.

After conductive a comprehensive review, De Oliveira C. et al. [8] highlight the significant potential of retrofitting buildings with active and passive strategies to improve energy efficiency and sustainability. In particular, building envelope insulation, HVAC system improvements, and renewable energy integration were found to be the most effective, contributing to energy savings of 30% to 60% in most case studies. Renewable energy sources, such as photovoltaic systems, demonstrated the ability to reduce grid energy consumption by up to 100%, making some buildings nearly self-sufficient.

In order to convert a condominium into an energy community, Minuto F. et al. study [9] offers a number of retrofit scenarios. Rooftop photovoltaic (PV) systems were found to be the most advantageous retrofit choice. This led to a 12% increase in energy efficiency and a 23% decrease in CO2 emissions in the building industry. Furthermore, up to 90% more self-consumption was made possible by battery storage devices, which increased the alignment of patterns of generation and consumption.

Shu L et al. study [10] emphasizes that smart and connected communities' retrofits have the potential to reduce global energy consumption by 60–80% and CO2 emissions by 30%,

particularly in developed regions. The large-scale retrofitting of buildings to integrate smart technologies, renewable energy systems, and enhanced energy management practices is crucial for achieving these reductions. The research identifies four primary research areas: building construction, mechanical systems, electrical systems, and human-centered design, each offering distinct approaches to achieving sustainability goals through retrofitting.
The study also outlines that retrofitting buildings within smart communities can lead to improved energy efficiency and sustainability at the community level.

Oraiopoulos A. et al [11] demonstrate that building retrofits, particularly when combined with urban development and climate change mitigation, can significantly reduce energy demand in Swiss communities. The results indicate that under the success retrofit scenario, energy demand can be reduced by 45.6% by 2040.

Rethnam O. et al. [12] study demonstrates that transitioning residential buildings to net-zero energy communities through rooftop solar PV installations can cover nearly 90% of the community's energy demand. In contrast, under current Energy Conservation Building Code standards, individual building compliance alone cannot achieve similar outcomes. The proposed rooftop solar strategy yielded a simple payback period of less than 8 years, proving its economic feasibility.

Similar conclusions were reached by Wills A.et al. [13], meaning that a neighborhood can achieve significant energy savings and carbon reductions by implementing thorough building retrofits and integrating renewable energy sources to transition to net-zero energy. In particular, the community-scale retrofitting, which included installing rooftop solar PV systems and improving envelope insulation, decreased energy consumption by 69% and greenhouse gas emissions by 95%. Installing solar PV panels on the entire accessible roof area produced sufficient energy to balance the usage of 1980s-era single-family dwellings.

Retrofitting existing buildings with modern technologies and renewable energy sources is crucial for reducing energy consumption, given that many older structures lack adequate insulation, energy-efficient windows, and heating systems.

This article explores various strategies and technologies employed in retrofitting buildings to promote energy communities. It examines the role of regulatory and economic frameworks in supporting these initiatives and presents several case studies showcasing the benefits and challenges of retrofitting, such as increasing energy self-sufficiency, reducing greenhouse gas emissions and achieving significant economic savings while addressing long-term sustainability and largescale actions.

2 Technologies and Strategies for Retrofitting

One of the primary technologies used in retrofitting is advanced insulation materials. These materials enhance the thermal performance of buildings, reducing heat loss in the winter and keeping interiors cooler in the summer. Conduction, convection, and radiation are the three heat gain/loss mechanisms that affect building envelope energy retrofit. However, convectional heat transfer should be minimized to increase airtightness which has an important impact on energy losses [14]. Various insulation options are available, including rigid foam boards, spray foam, and cellulose made from recycled paper products. Each type has its advantages, and the choice depends on the specific building context and local climate conditions.

Incorporating renewable energy sources is another critical aspect of retrofitting. Some of the most used techologie for renewable energy in building retrofit are solar thermal collectors, photovltaic systems, thermosyphon and solar thermal forced circulation and wind power [15]. Solar photovoltaic (PV) panels are increasingly popular for generating electricity. The most significant renewable resource at the building cluster level is solar energy, particularly in the context of EU building retrofits, which are directly impacted by the city's building density. The majority of renewable energy source solutions are sourced from solar and air resources [16]. With technological advancements, these systems have become more efficient and affordable. Furthermore, solar thermal systems can be integrated to provide hot water, further reducing reliance on fossil fuels. Wind turbines are also viable options, particularly in suitable locations, contributing to the overall energy independence of the community.

Smart energy management systems and devices play a meaningful role in optimizing energy consumption in retrofitted buildings. The characterization of a building as “smart” or “intelligent” has gained a lot of popularity in the recent years but without a well-established definition of the concept. Some of the key features of this notion are buildings’ capability to respond to external climate conditions, buildings’ response to signals/information coming from the grid, t The capability to monitor building operations in real time for fault detection or predictive maintenance and the ability of a building to facilitate real-time communication between users and installed technologies [17]. These systems utilize sensors, controls, and software to monitor energy use and manage appliances, heating, and cooling systems. By collecting and analyzing data, these systems can make real-time adjustments to improve efficiency and reduce costs. Additionally, integrating energy storage solutions, such as batteries, allows buildings to store excess energy production for later use, enhancing resilience during peak demand periods.

Another innovative strategy involves the use of green roofs and walls, which can be considered under the so named Nature-based solutions (NBS) able to improve energy efficiency while providing additional benefits such as stormwater management and improved air quality. These living systems not only insulate buildings but also reduce the urban heat island effect, contributing to healthier urban environments.

Table 1 presents in brief the main technologies for retrofitting together with their impact.

Table 1. Main technologies for buildings’ retrofitting

Technology/ Strategy	Pros	Cons	Impact on Old Buildings	Financial Aspects	Difficulty for Implementation
Advanced Insulation Materials	Improves thermal efficiency, reduces heating and cooling demands by up to 40%	Can be expensive, with costs ranging from 25 to 60 EUR per square meter for high-performance insulation	Significant reduction in energy consumption (up to 40%), especially for poorly insulated structures	Upfront investment can be recovered in 5-10 years through energy savings	Moderate to High - Requires professional installation and structural modifications
Solar Photovoltaic (PV) Panels	Generates clean, renewable energy, reducing dependence on fossil fuels	High initial costs, with an average installation price	Can reduce electricity bills making buildings partially energy independent	Payback period ranges usually 8-12 years depending on energy prices and location	High - Dependent on location and requires extensive rooftop installation
Heat Pumps	Efficiently uses ambient heat, reducing energy usage for	High costs together with ongoing	Improves heating efficiency, especially in older buildings,	Payback period generally between 7-12	Moderate - Requires professional installation and

	heating by 30-60%	maintenance requirements	with savings up to 60% on heating costs	years, with substantial long-term energy savings	regular maintenance
Smart Energy Management Systems	Optimizes energy use through real-time monitoring and can reduce energy costs by 10-20%	Initial setup costs for systems can range from 4,250 to 8,500 EUR, depending on the building size	Greatly improves energy efficiency, reducing overall energy use by 10-20% in older systems	Initial investment recouped in 5-7 years through reduced energy consumption	Moderate - Complex to integrate with existing systems but scalable and effective
Green Roofs and Walls	Enhances building insulation, reduces urban heat island effect, and provides up to 25% reduction in energy demand	Installation costs range from 85 to 220 EUR per square meter, with additional maintenance costs	Reduces energy consumption by up to 25%, while also improving air quality	Initial costs are high, but long-term environmental and energy savings make it viable within 10-15 years	High - Requires structural analysis, professional installation, and ongoing maintenance

Case studies of successful retrofits highlight the potential of these technologies and strategies. For instance, several cities worldwide have implemented retrofitting programs that include a combination of energy-efficient upgrades, renewable energy installations, and community engagement initiatives. These projects demonstrate the feasibility and effectiveness of transforming existing buildings into contributors to positive energy communities.

3. Economic and Regulatory Framework

Understanding the economic implications of retrofitting is essential for each type of stakeholder involved in the process. The initial costs associated with retrofitting can be significant; however, long-term savings on energy bills or reduced cost of maintenance/replacement of the implemented solutions often outweigh these first investments. Various financial models, including energy performance contracting, allow property owners to fund retrofits through savings generated by reduced energy consumption. Retrofitting existing buildings can lead to significant cost savings in feasible payback period. One case study in eastern India demonstrated how energy retrofitting measures, such as replacing ceiling fans with brushless direct current (BLDC) fans and using LED lighting, resulted in significant annual energy and financial savings [18]. The payback period for retrofitting measures varies depending on the technologies used, with faster returns for efficient lighting and HVAC systems compared to more extensive building envelope modifications [19-20].

Policymakers have focused on technical challenges, but to address economic and behavioral barriers, more comprehensive policies are needed. Greater emphasis should be placed on government efforts to raise public awareness of energy systems and the environmental impact of behavior

The economic viability of retrofitting to achieve near Zero Energy Buildings (nZEB) or net-zero carbon (NZC) standards is increasingly being prioritized, especially in office and public buildings, where energy efficiency measures combined with renewable energy sources provide a balance between cost savings and energy consumption (Ibrahim, 2024), [21].

Incentives, subsidies and financing play a crucial role in promoting retrofitting efforts. Governments at various levels offer financial support through low interest loans, tax credits, grants, and rebates, making retrofitting more accessible to homeowners and businesses. Additionally, some jurisdictions have established low-interest loan programs specifically for energy efficiency upgrades, further encouraging participation. By reducing financial barriers, these initiatives enable more building owners to invest in retrofitting.

Regulatory frameworks also influence the pace and feasibility of retrofitting projects. Building codes and standards often dictate the minimum energy efficiency requirements for new constructions and renovations. Implementing stricter standards can drive demand for retrofitting existing buildings to meet or exceed these requirements. Moreover, energy efficiency regulations can be tied to property assessments, incentivizing owners’ agreement and reducing defaulters (e.g. in condominium or multifamily buildings) to improve their buildings to increase their value. Various regulatory codes are driving retrofitting initiatives, such as the Energy Conservation Building Code (ECBC) in India, which mandates energy-efficient building designs. Adopting ECBC standards in retrofitting projects helps achieve up to 30% energy savings. In Europe, regulations like the last version of Energy Performance of Buildings Directive (EPBD) push for retrofitting to improve energy efficiency and carbon neutrality. The Renovation Wave targets doubling renovation rates by 2030 and aims for buildings to meet higher energy efficiency standards, including NZEB. The UK but also other European countries are implementing frameworks that focus on life-cycle carbon emissions, integrating retrofitting into national strategies for achieving NZC goals by 2050 [22].

The social impacts of retrofitting should not be overlooked. Nevertheless, enhanced building performance contributes to improved indoor air quality and thermal comfort, positively affecting occupants' health and well-being. That means less costs also on the public national’s healthcare system. Furthermore, community engagement in retrofitting projects can foster a sense of ownership and responsibility among residents, leading to increased awareness and support for sustainable practices.

While retrofitting offers substantial energy and cost benefits, challenges remain in scaling solutions to larger, multi-building projects. The complexity of multi-building retrofitting often requires tailored and reliable solutions that vary depending on building types, climates, and regulatory environments. There is a need for unified international guidance on energy retrofitting standards, as current differences in definitions and requirements hinder comparability and scalability of retrofitting projects across regions. Another challenge is that individual actors lack strong enough incentives to invest in energy efficiency retrofits, despite the significant societal benefits, due to factors like lack of information and long payoff periods. This affects the critical mass of retrofit work required to achieve a sizable amount of the energy savings [23].

Overall, the interplay of economic factors, regulatory frameworks, and social impacts is crucial for understanding the landscape of building retrofits. By examining successful examples, we can identify best practices and strategies for overcoming challenges in promoting positive energy communities.

4. Discussions and Conclusions

The integration of smart technologies, such as the Internet of Things (IoT), will continue to advance energy management capabilities. These technologies enable real-time monitoring and optimization of energy use, paving the way for more efficient buildings that can adapt to changing conditions and demands.

Additionally, the focus on decarbonization will drive innovation in retrofitting strategies. As countries need to meet climate goals, retrofitting existing buildings will be essential to reducing greenhouse gas emissions. The development of new materials and construction techniques (e.g. CO2 free) will play a crucial role in this transition, enabling buildings to operate more sustainably.

Community engagement and participatory approaches will also be vital for the success of positive energy communities. Encouraging collaboration among residents, local governments, and businesses can foster a shared vision for sustainability. By involving stakeholders in decision-making processes, communities can modify retrofitting initiatives to meet their specific needs and preferences. That reveals the need for data and tools supporting multicriteria analysis, and enabling decisions based on the assessment of potential impacts scenarios. Such data and tools will support and guide citizen and planners towards a sustainable design while recommending alternatives from a comprehensive perspective and suggesting the best actions to be put in place targeting such priorities.

Both the impact evaluation of each measure and the comparison of each scenario is key, and mean the need of a multiple performance approach, credible assessing methods for different KPIs (i.e. energy, cost or CO2 emissions) including additional co-benefits (e.g. also social acceptance).

In conclusion, large scale retrofitting buildings is one of the most important components of creating positive energy communities. By implementing advanced technologies, innovative strategies, and supportive regulatory frameworks, we can significantly enhance the energy performance of existing buildings. Significant business models (e.g. Turnkeys or Public-Private-Partnership) are successful ways to overcome most of the barriers during the implementation process, and prelude to innovative renting/leasing solutions to project financing.

Future research should continue to explore new technologies, assess the effectiveness of retrofitting programs, and address the challenges of implementation. By working collaboratively, we can pave the way for a sustainable future that prioritizes energy efficiency and environmental protection.

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