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Review

Review: The Economics Landscape for Building Decarbonization

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Abstract: As efforts to mitigate climate change become increasingly urgent, the need to address the environmental impact of the built environment has gained significant attention. Buildings, as major contributors to Greenhouse Gas (GHG) emissions, have a substantial embodied and operational carbon footprint resulting from their construction materials, practices, and lifetime operation. This paper examines the economic landscape of strategies and policies aimed at reducing the embodied and operational carbon footprint of buildings on a global scale, with specific case studies from various national contexts. It delves into various innovative approaches, including economic analysis techniques, market instruments, market demands, and the role of government incentives to reduce the carbon footprint of buildings. The study highlights the crucial role of government policies, financial incentives, and market forces in promoting sustainable practices and fostering the adoption of low-carbon alternatives. By shedding light on the economic dimensions of reducing the carbon footprint of buildings, this research aims to facilitate informed decision-making by policymakers, engineers, and other stakeholders, ultimately contributing to a more sustainable and climate-resilient built environment.

Keywords: buildings decarbonization; climate change; economic landscape; government programs; market forces

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1. Introduction

As the global community faces the urgent challenges of climate change and its far-reaching impacts, the imperative to decarbonize various sectors of anthropogenic activity has taken center stage. The built environment plays a pivotal role due to its substantial contribution to Greenhouse Gas (GHG) emissions. Buildings are not only major consumers of energy but also responsible for a significant portion of carbon emissions resulting from their construction, operation, and eventual decommissioning [1–3]. To mitigate the adverse effects of climate change, a paradigm shift toward building decarbonization has emerged as a critical strategy [4–8].

Building decarbonization refers to the ambitious goal of significantly reducing or eliminating the carbon emissions associated with all aspects of the built environment, while concurrently enhancing energy efficiency and sustainability. Achieving this goal involves a comprehensive transformation that encompasses both existing and future buildings, their energy systems, materials, and practices [6,9–11].

The economic case for building decarbonization is multifaceted. On the one hand, there are upfront costs and investments required for implementing energy-efficient technologies, renewable energy systems, and sustainable construction practices [12]. On the other hand, it is essential to recognize that these investments yield substantial long-term benefits. Reduced energy consumption, lower operational costs, and increased property value are just a few of the tangible advantages for building owners and occupants [10,13,14].

Moreover, the transformation toward a decarbonized built environment has the potential to create new economic opportunities and industries. Innovative green technologies and services will witness burgeoning demand, fostering job creation and stimulating economic growth. As the transition gains momentum, the economic landscape will evolve, influencing supply chains, market dynamics, and consumer preferences [15,16].

Yet, the path to building decarbonization is not without challenges. Obstacles such as existing infrastructures, regulatory barriers, and financial constraints demand thoughtful strategies and collaboration across stakeholders. Public–private partnerships, innovative financing mechanisms, and supportive policy frameworks will be instrumental in driving widespread adoption and ensuring equitable access to decarbonization initiatives [16–19].

In summary, building decarbonization is not merely an environmental imperative; it is a call to action that transcends industries, governments, and societies. Through a shared commitment to reducing carbon emissions and embracing innovation, it is possible to build a resilient and prosperous future while safeguarding our planet for generations to come.

This paper provides a review of the economic landscape surrounding building decarbonization, exploring the challenges, opportunities, and potential solutions in the pursuit of a low-carbon built environment. By examining the intricate interplay of market forces, technological innovations, government policies, and societal attitudes, this study aims to paint a holistic picture of the economic drivers and barriers that shape the trajectory of building decarbonization efforts. Also, this paper endeavors to shed light on the intricate economic dimensions of building decarbonization, examining case studies, best practices, and real-world examples from various regions and building types. By understanding the economic implications of decarbonization, it is possible to foster informed decision-making, accelerate transformative actions, and collectively embrace a sustainable future for the built environment.

1.1. Significance of Carbon Footprint of Buildings

The carbon footprint of buildings is composed of embodied carbon, which includes emissions throughout a building's life cycle from material extraction to disposal, and operational carbon, which accounts for emissions during day-to-day building operations (Figure 1).

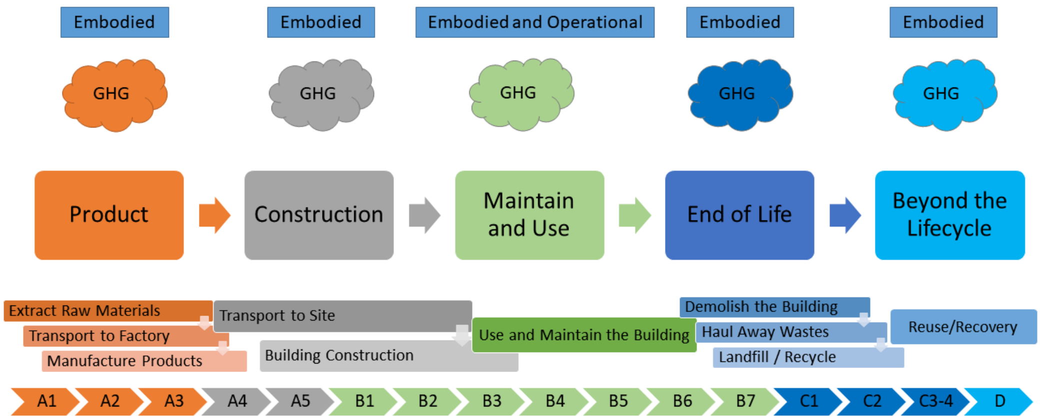

Figure 1. Building Greenhouse Gas (GHG) emissions throughout life cycle stages (A1: raw material acquisition, A2: transportation of materials, A3: manufacturing and pre-fabrication, A4: transport to site, A5: construction, B1: building use, B2: operational energy use, B3: water use, B4: maintenance, B5: replacement of building components, B6: energy efficiency measures and renewable energy integration, B7: water efficiency measures, C1: renovation and demolition, C2: transportation to and from the building, C3-4: transportation of goods and services, D: reuse/recovery).

Buildings and infrastructure are commonly evaluated for their operational carbon emissions resulting from energy consumption during their lifetime. However, embodied carbon can be a significant portion of a project's total carbon footprint and should not be overlooked. As illustrated in Figure 2, both operational and embodied carbon emissions are important; hence, the mitigation of both is crucial for achieving carbon neutrality and sustainability [10,20–23]. While operational carbon emissions have traditionally been the focus of decarbonization strategies, embodied carbon emissions are gaining increasing attention due to their significant impact, particularly in modern buildings that are designed to be energy efficient and have a long lifespan. Reducing the embodied carbon emissions often involves selecting sustainable materials and construction methods, while reducing the operational carbon emissions focuses on improving energy efficiency and utilizing renewable energy sources. Both aspects are essential for achieving a comprehensive decarbonization strategy in the built environment. Also, embodied carbon has long-term implications (https://www.eia.gov/outlooks/ieo/ (accessed on 17 November 2023)). Once emitted, GHGs stay in the atmosphere for an extended period, contributing to global warming and climate change [24–29]. Figure 3 shows the varying levels of carbon emissions associated with different construction materials and constitute the embodied carbon emissions for buildings.

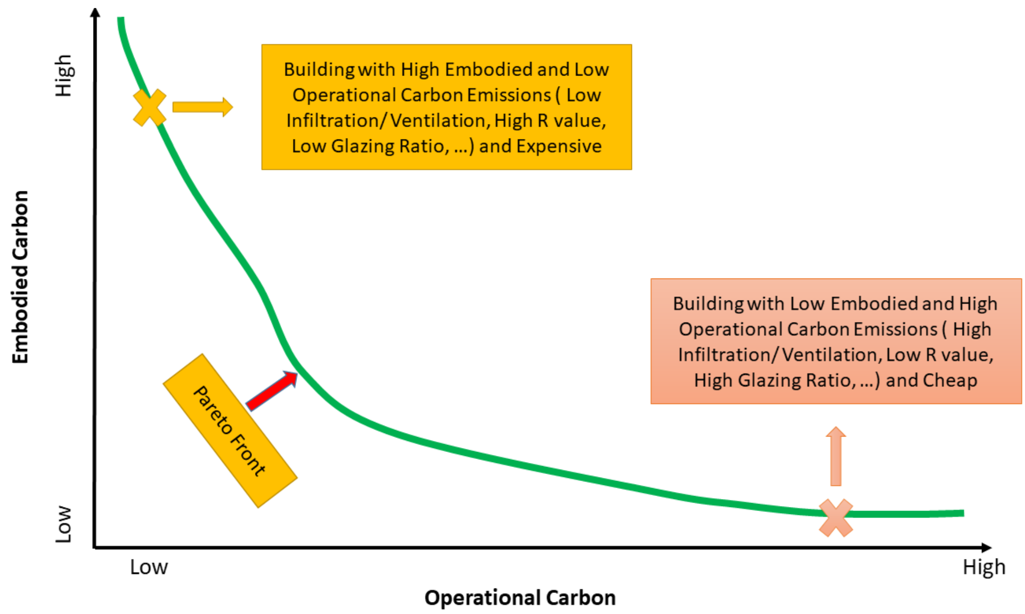

Figure 2. Embodied carbon versus operational carbon emissions.

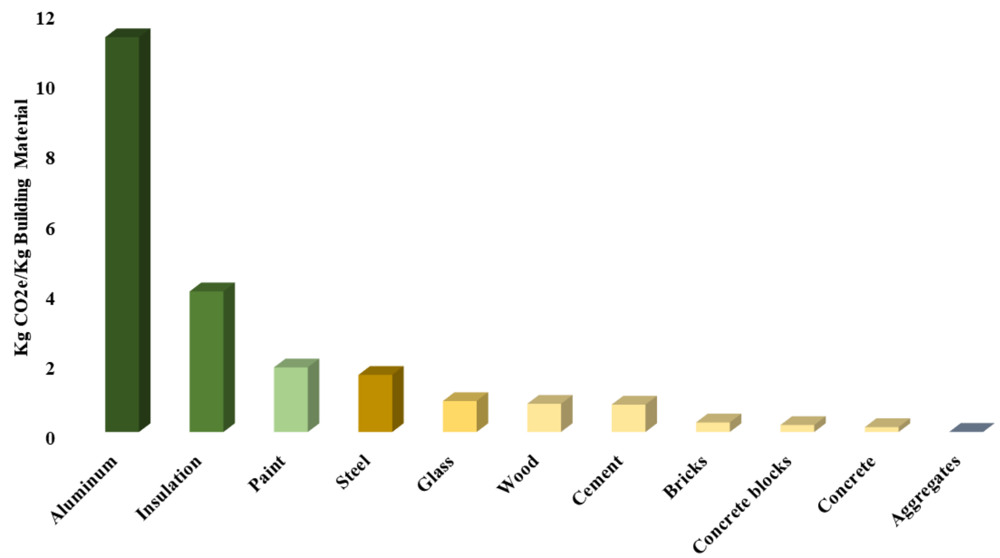

Figure 3. Embodied carbon emissions of selected construction materials (data source: [30]).

1.2. Economics of Building Decarbonization

Considering economic analysis in building decarbonization allows for a comprehensive assessment of the total costs related to a project. Through assessing the carbon emissions for the entire life cycle of materials and infrastructure, decision-makers can identify opportunities to optimize costs and minimize long-term environmental impacts. This analysis enables a more holistic understanding of the economic implications and helps identify cost-effective solutions [31].

Failing to account for building decarbonization in economic analysis, and vice versa, can lead to potential risks and financial liabilities in the future. As governments and organizations worldwide implement policies and regulations to reduce carbon emissions, projects that ignore building decarbonization may face penalties, restrictions, or even the need for costly retrofits to meet the changing environmental standards. Integrating building decarbonization analysis into economic assessments helps manage these risks and ensures long-term project viability [32]. Likewise, improper economic analysis and measures may result in costly building decarbonization efforts, beyond what is necessary.

The objective of this paper is to provide a review of the economic landscape for building decarbonization efforts. This study reviews the government programs and market forces, with a focus on understanding the economic implications, challenges, and opportunities associated with transitioning the built environment to a low-carbon and sustainable future. This study attempts to find some answers to the following questions:

- What are the strengths and limitations of conventional economic analysis techniques and economic instruments for building decarbonization?
- What are the key economic drivers and incentives for building decarbonization?
- How do different economic models and policy frameworks impact the feasibility and scalability of building decarbonization projects?
- What are the lessons learned from case studies (both successful and failed) and best practices in the economics of building decarbonization?
- How can economic instruments, such as carbon pricing, subsidies, and tax incentives, be utilized to accelerate building decarbonization?
- What is the role of government incentives and market demand in building decarbonization?

These research questions aim to guide the comprehensive exploration of the economic dimensions of building decarbonization, offering insights that can inform policy-makers, industry stakeholders, and researchers in their efforts for building decarbonization.

To develop the review, a systematic methodology was employed. This involved conducting a thorough literature search across academic databases using keywords such as “building decarbonization”, “economic analysis”, and “carbon footprint”. Selected sources, prioritizing peer-reviewed articles, government reports, and industry publications, were screened for their relevance. Data extraction focused on identifying the economic strategies, policies, and market instruments aimed at reducing the carbon footprint in buildings. Successful and failed case studies were examined to understand the efficacy of different approaches. Analyzing these findings highlighted key themes, such as the role of government incentives, market demands, and economic analysis techniques in promoting sustainable building practices. The synthesis of this information was structured to provide a comprehensive overview of the economic landscape, emphasizing the interplay between policy frameworks, financial incentives, and market dynamics.

This paper is organized into the following sections to comprehensively address the economic landscape for building decarbonization. Section 2 provides an overview of the established methods in economics that may be used in building decarbonization analysis. Section 3 delves into a range of economic tools and strategies specifically intended for building decarbonization. Subsections within this part cover the Social Cost of Carbon (SCC), carbon pricing, subsidies, energy performance standards, building certificates, public–private partnerships, and research and developments funding. In Section 4, this study explores the dynamic interplay between government policies, market forces, and incentives in the context of building decarbonization. Section 5 offers real-world examples, illustrating successful and failed applications of economic strategies. Section 6 critically assesses the challenges and obstacles in implementing these low-carbon solutions. Finally, Section 7 provides the lessons learned from the review and a forward-looking perspective on potential avenues for future research and action. This structured approach aims to guide readers through a comprehensive analysis of the economic dimensions of building decarbonization and the various economic instruments available for its advancement.

2. Conventional Economic Analysis

2.1. Conventional Economic Analysis Techniques

Conventional economic analysis techniques are commonly deployed to evaluate the feasibility and likely benefits of building decarbonization initiatives. These techniques help decision-makers evaluate the costs, benefits, and overall economic viability of various strategies aimed at reducing carbon emissions in the construction and operation of buildings. Figure 4 summarizes some key conventional economic analysis techniques used for building decarbonization.

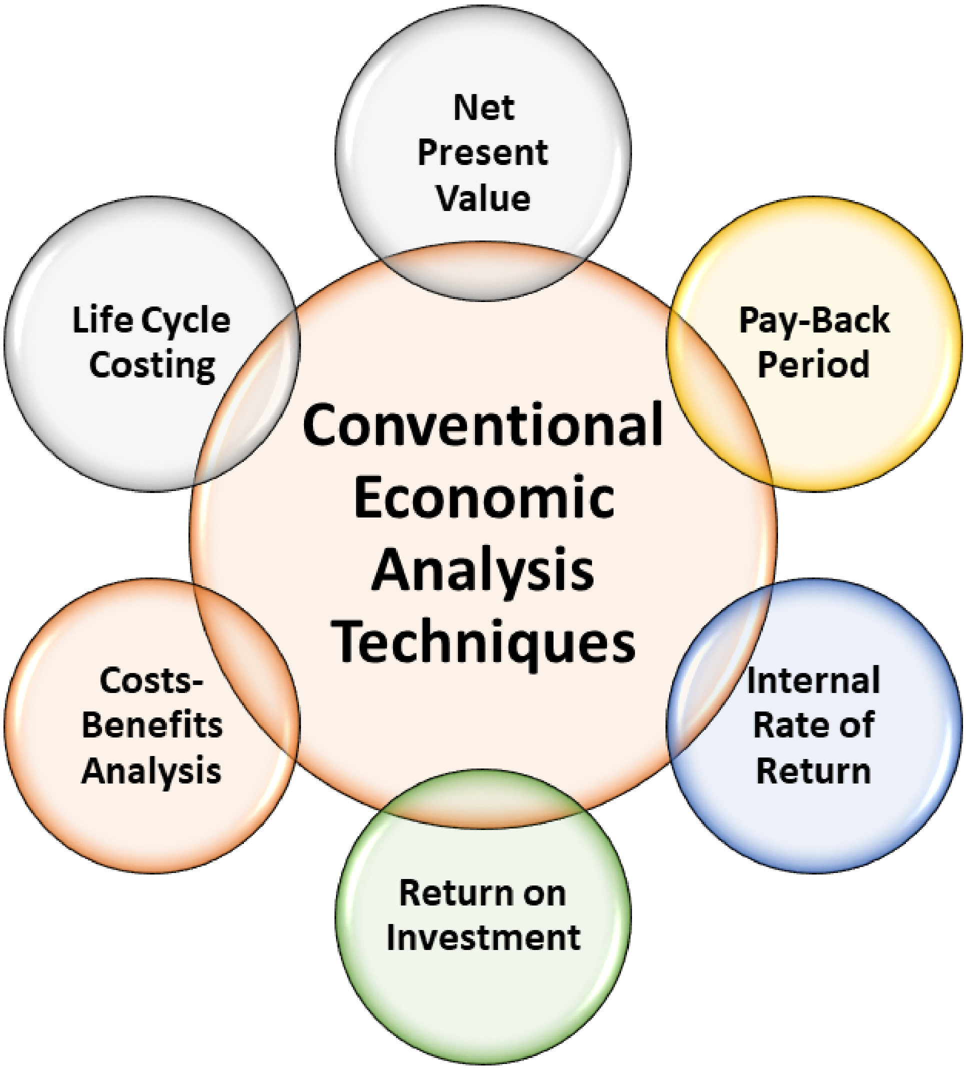

Figure 4. Conventional economic analysis techniques.

2.1.1. Net Present Value

The Net Present Value (NPV) is a measure used to asses the profitability and financial feasibility of a financial alternative. It considers the time value of money by discounting cash flows over a time horizon to their present value. NPV calculates the net worth of expected cash inflows and outflows over the life of the investment, adjusted for the cost of capital using a discounting rate. NPV can be calculated using:

$$NPV = \sum \frac{\text{Cash Flow}}{(1 + \text{Discount Rate})^{\text{Period}}}. \quad (1)$$

NPV analysis empowers decision-makers to compare various investment alternatives and assess their financial attractiveness. A higher NPV suggests a more financially favorable alternative, as it signifies a higher net worth of cash inflows relative to the initial expenditure. Nevertheless, it is important to consider other measures alongside NPV, such as risk, market conditions, and qualitative considerations. NPV analysis ought to be employed in combination with other financial metrics, such as the Internal Rate of Return (IRR), payback period, and sensitivity analysis, to make well-informed investment decisions.

2.1.2. Pay-Back Period

The payback period is a measure that calculates the time required for an investment or project to recover its initial cost or investment outlay. It quantifies how quickly an investment generates cash inflows to cover the initial, and perhaps large, expenditure. To calculate the payback period, these steps are followed: (1) determine the initial investment, (2) estimate the expected cash inflows, (3) subtract cash inflows from the initial investment, and (4) determine the payback time period. The payback period is expressed in years, months, or other relevant time units.

2.1.3. Internal Rate of Return

The Internal Rate of Return (IRR) is a measure deployed to assess the viability of an investment alternative. In the context of building decarbonization, it is used to evaluate the financial feasibility or benefits of implementing energy-efficient and carbon reduction measures in buildings.

The IRR in building decarbonization is calculated by considering the costs associated with implementing these measures and the expected savings or benefits generated over time. The IRR considers the time value of money using a discounting rate for the NPV of all cash flows (costs and savings) canceling one another for a given time horizon. In other words, it is the rate at which the project breaks even, making it financially feasible and attractive for investors or building owners.

2.1.4. Return on Investment

Return on Investment (ROI) is a measure to assess the viability and efficacy of a financial alternative. It quantifies the return or gain produced relative to the cost of the investment. ROI is typically calculated as a percentage or ratio.

ROI is commonly used to measure the profitability and compare the financial outcome of capital expenditures. It allows for easy comparison by standardizing the return in percentage terms. A higher ROI generally signifies a more favorable investment, as it predicts a higher return in comparison to the cost. It is recommended to use ROI in combination with other financial evaluation measures, such as NPV and IRR, to make more informed investment choices.

2.1.5. Life Cycle Costing

Life Cycle Costing (LCC) is a financial analysis method that considers the total cost of a product, project, or asset throughout its entire life cycle. It involves assessing and quantifying all costs associated with the life cycle stages, including acquisition, operation, maintenance, and disposal. The key steps involved in conducting an LCC analysis are as follows: (1) identify the life cycle stages, (2) identify cost components, (3) assign cost values, (4) apply discounting, and (5) calculate life cycle costs [13,33,34].

2.1.6. Cost–Benefit Analysis

Cost–Benefit Analysis (CBA) is a method used to assess the economic desirability of a project, investment, or decision. It compares the costs and benefits associated with a particular course of action to determine if the benefits outweigh the costs and if the project or investment is economically justified. The steps involved in conducting a CBA are as follows: (1) identify the project or decision, (2) identify costs, (3) identify benefits, (4) assign monetary values, (5) apply discounting, (6) calculate the net present value, and (7) perform sensitivity analysis [35,36].

2.2. Strengths and Limitation of Conventional Economic Analysis Techniques for Building Decarbonization

Conventional economic analysis methods, such as NPV and IRR, provide metrics to assess the financial viability and attractiveness of investments for building decarbonization. They help quantify the return on investment and support decision-making about resource allocation. Moreover, such techniques allow for sensitivity analysis, which helps in understanding the impact of changes in key parameters and assumptions on the economic outcomes. This provides insights into the viability of analysis and helps identify critical factors influencing the financial performance of decarbonization measures [37].

However, economic analysis of building decarbonization requires extensive data on costs, emissions, energy consumption, and other relevant factors. Collecting accurate and comprehensive data can be challenging and time-prohibitive, especially for complex supply chains and diverse industries. There is inherent uncertainty and variability in estimating the carbon intensities and associated costs. Factors such as variability in materials, production processes, and supply chain dynamics can introduce uncertainty into the economic analysis [38].

Conventional methods such as the discounted cash flow analysis consider the time value of money by discounting future costs and benefits to their present worth. However, determining an appropriate discounting rate for environmental considerations is very controversial. Higher or lower discounting rates can favor or disfavor certain choices [39].

Furthermore, the strengths of LCC lie in its comprehensive approach, enabling stakeholders to evaluate the long-term financial benefits of sustainable practices, such as energy efficiency and reduced emissions, which can lead to significant cost savings and environmental benefits. However, LCC has limitations, including the difficulty of accurately predicting future costs and benefits due to uncertain factors like energy prices, technological advancements, and regulatory changes. Additionally, LCC often requires detailed data and sophisticated modeling, which can be resource-intensive and complex, potentially limiting its accessibility and applicability for all projects.

Not all impacts of GHG emissions may be easily monetized or quantified in financial terms. Some environmental and social benefits or costs may be challenging to translate into monetary values, limiting the comprehensiveness of the economic analysis. Conventional economic analysis techniques primarily focus on financial dimensions and may not fully capture non-economic factors, such as social equity, public health, or ecological considerations. These factors are important for holistic decision-making but may require additional assessment methods beyond conventional economic techniques [40].

There is currently no universally accepted standard methodology for conducting economic analysis specifically for building decarbonization. This can result in variations in approaches, assumptions, and results, making it challenging to compare studies or establish consistent guidelines.

3. Economic Instruments for Building Decarbonization

Reducing building carbon emissions requires a combination of economic instruments and strategies [15,41]. Figure 5 shows some effective economic instruments that can be utilized. It is important to note that Figure 5 provides a significant, yet not exhaustive, collection of these instruments, and may not include all possible cases of each intervention option.

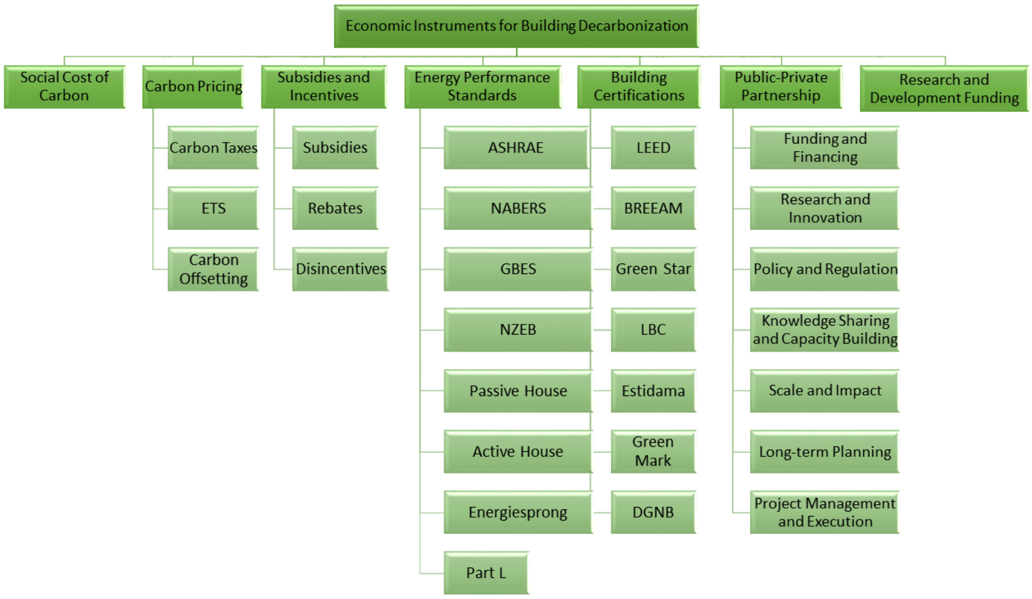

Figure 5. Economic instruments for building decarbonization (ETS: Emissions Trading System, ASHRAE: American Society of Heating, Refrigerating and Air-Conditioning Engineers, NABERS: National Australian Built Environment Rating System, GBES: Green Building Evaluation System, NZEB: Net Zero Energy Building, LEED: Leadership in Energy and Environmental Design, LBC: Living Building Challenge, DGNB: German Sustainable Building Council).

3.1. Social Cost of Carbon

The Social Cost of Carbon (SCC) is a metric used to calculate the economic cost associated with each additional Tonne of equivalent carbon dioxide (CO_2e) emissions released into the atmosphere. It represents the value of damage to society caused by the unit of emissions, considering the long-term impacts. Governments and policymakers use SCC to make informed decisions regarding climate change mitigation policies, regulations, and investments. By assigning a price to carbon emissions, SCC aims to internalize the external costs of GHG emissions and create economic incentives for businesses and individuals to reduce their carbon footprint [42,43].

One method of calculating SCC is by determining the current value of the difference between damages resulting from climate change along a reference climate trajectory and damages along the same trajectory with an additional incremental release of CO_2e emissions. Over the past thirty years, the SCC has been estimated multiple times using a variety of assumptions concerning uncertain variables like the social discount rate, economic growth, and climate sensitivity. Recent estimations place the SCC between approximately USD −10 to USD 1000 per Tonne of CO_2e [44–47].

Among the up-to-date SCC assessments are those computed by the US Environmental Protection Agency (USEPA). For the year 2020, the values stand at USD 12, USD 42, and USD 62 per Tonne CO_2e emitted, for discount rates of 5%, 3%, and 2.5%, respectively. Various alternative techniques have been utilized throughout the years to estimate the SCC, encompassing more advanced treatments of time, risk, and equity preferences, as well as incorporating more recent representations of climate damage and feedback. A recent survey involving climate scientists and economists arrived at an average SCC of roughly USD 150–200 per Tonne CO_2e [48].

The global estimates of SCC hide significant variations in the country-level SCC (CSCC). In Figure 6, the country-level social cost of carbon dioxide emissions is depicted, illustrating the estimated financial impact (in USD per Tonne CO_2) on different nations due to global warming. A value of zero indicates that the projected impact is negligible or minimal, while positive values suggest potential economic damages from climate change. Conversely, negative values indicate countries where there may be perceived economic benefits associated with global warming impacts. This analysis underscores the complex economic and environmental dynamics influencing carbon pricing strategies worldwide. Figure 6 illustrates the geographical pattern of CSCCs based on a baseline Socioeconomic Pathway (SSP) or Representative Concentration Pathway (RCP) scenario (SSP2-RCP6 with standard Burke, Hsiang and Miguel (BHM) specifications (2015)). Among countries, India exhibits the highest CSCC at USD 86 per Tonne CO_2e (ranging from 49 to 157). The United States follows with USD 48 per Tonne CO_2e (ranging from 1 to 118). Similarly, Saudi Arabia's CSCC is USD 47 per Tonne CO_2e (ranging from 27 to 86). Three other countries, Brazil, China, and the United Arab Emirates, have CSCCs above USD 20, USD 24, and USD 24 per Tonne CO_2e, respectively. Certain regions, including Northern Europe, Canada, and Russia, display negative CSCC values due to their current temperatures being below the optimal economic level. These findings are particularly sensitive within the analysis, as all countries have positive CSCC under the BHM long-run. Although 90% of the global population has a positive CSCC, the magnitude of CSCC varies based on scenarios and discount rates, and the relative distribution remains generally stable despite these uncertainties [43,44,46].

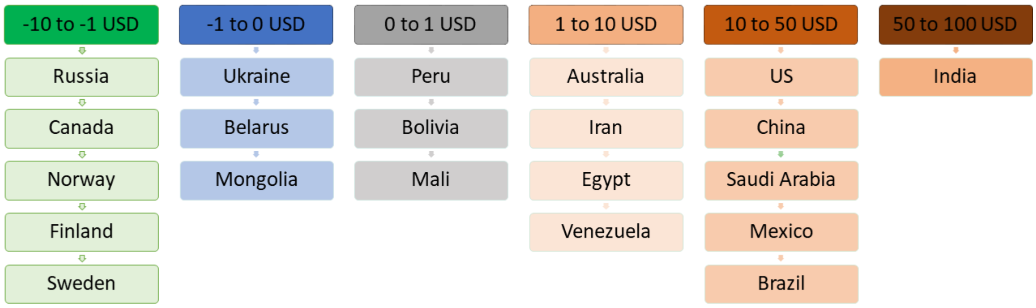

Figure 6. Country-level Social Cost of Carbon (CSCC); zero indicates minimal projected impact from global warming; positive values indicate potential economic damages; negative values suggest the potential economic benefits from global warming impacts (adapted from [43] and reproduced in simple conceptual form).

While SCC provides a valuable framework for understanding the costs of carbon emissions, it may not fully capture non-market impacts, such as the loss of biodiversity, cultural heritage, and ecosystem services. As a result, sensitivity analysis is often conducted to assess how changes in underlying assumptions and parameters can affect the SCC results [42,43].

Given the global nature of climate change, international cooperation is crucial in addressing the carbon emissions effectively. SCC can serve as a useful tool for countries to align their climate change policies and foster a collective effort to combat climate change. It is an essential concept in climate change economics, guiding efforts toward sustainability and promoting informed decision-making to address the challenges posed by climate change [43,47].

The SCC is a dynamic and evolving concept in the field of climate change economics. It represents a multidimensional approach to assessing the true cost of carbon emissions and the long-term impacts they have on society and the environment. By incorporating the externalities associated with climate change, such as increased frequency of extreme weather events, rising sea levels, disruptions to agriculture, and human health consequences, the SCC strives to provide a more accurate and comprehensive understanding of the real cost of carbon emissions [42,43,49].

One of the key challenges in calculating the SCC lies in addressing uncertainties. Climate change is a complex and interconnected system, and future impacts are subject to a range of factors, including technological advancements, policy decisions, population growth, and socioeconomic changes. Therefore, SCC estimates often involve sophisticated modeling techniques and scenario analyses to account for these uncertainties and potential future developments [43,44].

Moreover, the SCC has profound implications for the private sector, impacting investment decisions and risk assessments. Companies are increasingly recognizing the financial risks associated with carbon-intensive activities and the potential for regulatory changes and carbon pricing mechanisms. As a result, understanding the SCC and aligning corporate strategies with carbon reduction goals have become critical elements of sustainable business practices [42].

To ensure the continued relevance and accuracy of SCC estimates, ongoing research, data collection, and collaboration between scientists, economists, and policymakers are essential. As climate science progresses and our understanding of climate change impacts improves, SCC calculations are continually updated and refined to provide the most up-to-date and relevant information for decision-making.

3.2. Carbon Pricing

Implementing a carbon pricing mechanism, such as a carbon tax or Emissions Trading System (ETS), can provide incentive to building owners and developers to reduce their carbon emissions. By putting a price on carbon, it encourages the adoption of energy-efficient technologies and practices. Carbon pricing mechanisms are economic-based approaches designed to reduce GHG emissions [50,51]. Figure 7 provides a map of carbon pricing incentives in different regions and countries around the world. Below are three common types of carbon pricing mechanisms.

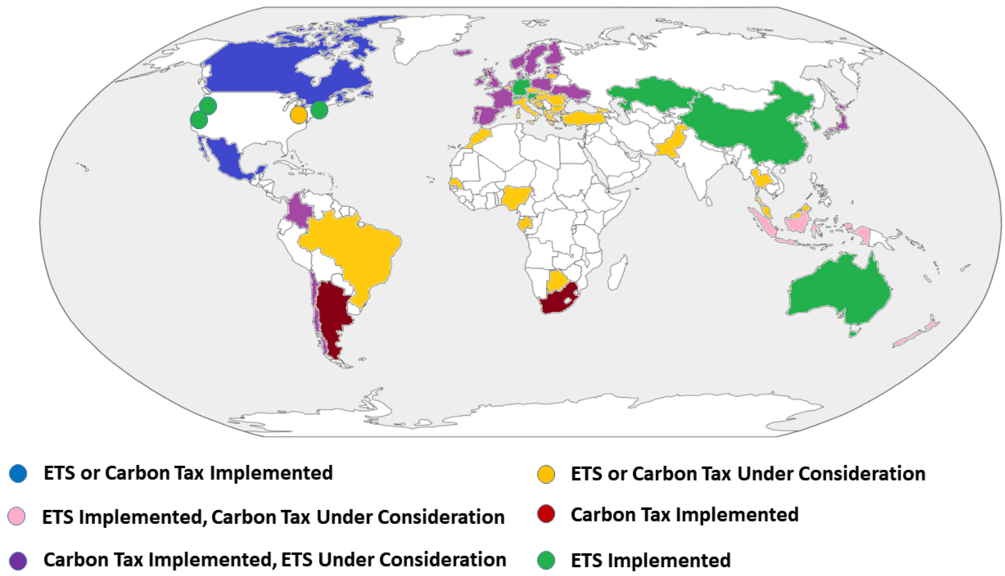

Figure 7. Summary map of regional and national carbon pricing initiatives (source: World Bank, "carbon pricing dashboard") [52].

3.2.1. Carbon Tax

A carbon tax imposes a direct fee or tax on the carbon composition of fossil fuels or other GHG-emitting activities. It assigns a financial cost to each Tonne of equivalent carbon dioxide (CO_2e) emitted. The tax rate can vary based on the carbon intensity of different activities or fuels. The goal is to make high-carbon activities more expensive and encourage companies and individuals to reduce their emissions. Table 1 shows the carbon taxes in different countries in Europe (2023). The revenue generated from carbon taxes can be allocated for various purposes, such as funding alternative energy initiatives or supporting climate mitigation and adaptation efforts.

Table 1. Carbon tax rates in different European countries per Tonne CO_2e in 2023 (source: World Bank, "carbon pricing dashboard") [52].

Country	Carbon Tax Rate (€per Ton of CO_2e)
Austria (AT)	32.50
Denmark (DK)	24.37
Estonia (EE)	2.00
Finland (FI)	76.92
France (FR)	44.55
Germany (DE)	30.00
Iceland (IS)	35.40
Ireland (IE)	48.45
Latvia (LV)	14.98
Liechtenstein (LI)	120.16
Luxembourg (LU)	44.19
The Netherlands (NL)	51.07
Norway (NO)	83.47
Poland (PL)	13.27
Portugal (PT)	23.90
Slovenia (SI)	17.30
Spain (ES)	14.98
Sweden (SE)	115.34
Switzerland (CH)	120.16
Ukraine (UA)	0.75
The United Kingdom (GB)	20.46

Implementing a carbon tax for building decarbonization comes with certain challenges that need careful consideration. One of the main worries is the likely regressive impact on building owners and tenants, as higher energy costs could disproportionately affect lower-income households and small businesses, potentially leading to financial strain and reduced affordability for energy-efficiency upgrades.

Administrative complexity is another issue, as accurately measuring and reporting building emissions can be challenging, particularly for older buildings with varying energy efficiency standards. This could create additional compliance burdens and costs for building owners.

The implementation of a carbon tax might also result in a slow pace of retrofitting, as some building owners could be hesitant to invest in energy-efficiency upgrades due to the added cost burden. This could hinder progress toward building decarbonization goals [53].

Competing financial priorities could also divert building owners' attention away from decarbonization initiatives. In the face of economic challenges, they may prioritize other investments over long-term sustainability efforts [53].

Another challenge stems from the diverse nature of building stock. Different building types, ages, and energy consumption patterns require tailored solutions. A uniform carbon tax might not adequately address the varying needs and complexities of different buildings. Furthermore, carbon taxes might incentivize short-term fixes or low-cost solutions in buildings to minimize immediate costs rather than promoting comprehensive and long-term sustainable upgrades [53].

Regional disparities are also a consideration, as the impact of a carbon tax on building decarbonization could vary significantly depending on the region's energy mix and availability of low-carbon alternatives. This could potentially exacerbate regional inequalities [53].

To address these challenges, policymakers need to carefully design carbon tax structures that provide incentives for building owners to invest in energy-efficient upgrades while ensuring social equity. Targeted support and incentives for different building categories are essential to accommodate the complexity of building types and energy needs.

3.2.2. Emissions Trading System (ETS)

ETS sets a limit (cap) on the total amount of GHG emissions allowed within a particular jurisdiction or industry sector. Allowances or permits representing a certain amount of emissions are issued and allocated to entities, such as companies. These entities can buy, sell, or trade their allowances in a carbon market. If an entity reduces its emissions below its allocated allowances, it can sell the surplus to entities that exceed their allowances. Figure 8 shows the carbon market pricing mechanism and the principles governing the formation of carbon prices, factors that influence them, and the mechanisms through which these prices are transmitted. The overall emissions cap is slowly reduced over a time horizon to lower emission targets. Cap-and-trade systems create a market for carbon allowances, providing financial incentives for entities to reduce their emissions cost effectively:

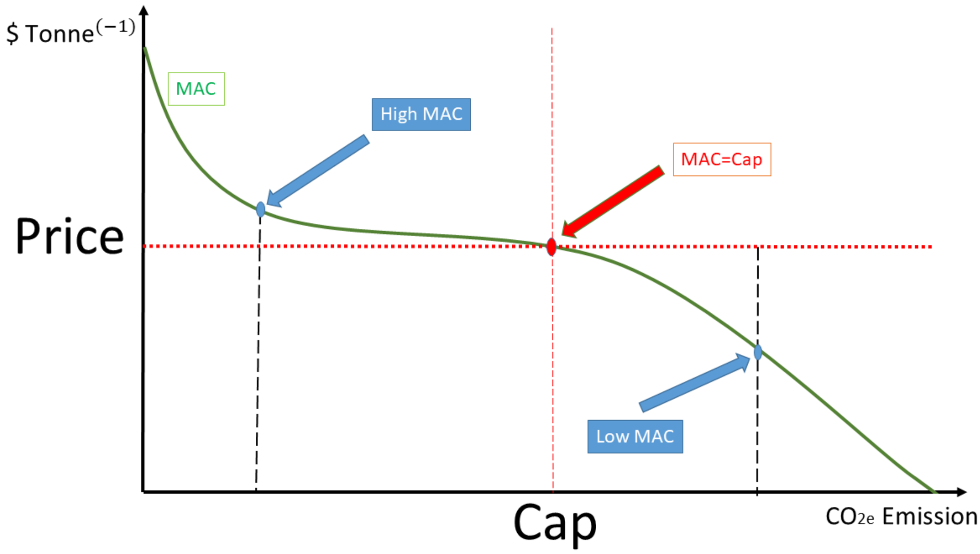

Figure 8. Cap-and-trade systems; MAC: Marginal Abatement Cost (adapted from [54] and reproduced in simple conceptual form).

Firstly, when determining the carbon price in a market, the enterprise will consider its Marginal Abatement Cost (MAC) (the cost associated with reducing one extra unit of GHG emissions) and the price elasticity of demand for carbon emission permits. If the MAC is lower or if the elasticity is higher, the price will be lower. Secondly, the carbon price will be impacted by the balance between the supply and demand of carbon permits in the Emissions Trading System (ETS). The supply of carbon permits is affected by the tightness of the cap, different methods of quota allocation, and the difficulty of issuing Certified Carbon Emission Reductions (CCERs). The demand for permits comes from the real emissions of emitting sources and is impacted by various factors including carbon price, traditional energy price, clean energy price, prices from other carbon markets, awareness of energy conservation and emission reduction, the price of carbon option futures in the carbon finance market, the number of enterprises in the carbon market, weather conditions, and political factors (Figure 9).

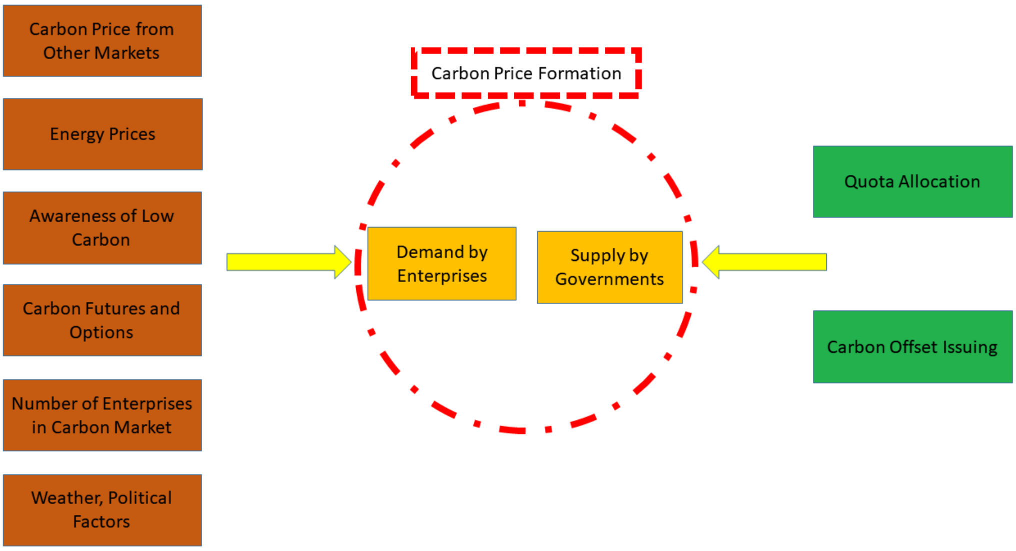

Figure 9. Carbon price formation (adapted from [54] and reproduced in simple conceptual form).

As shown in Table 2, governments have three approaches to implementing carbon pricing: (1) direct implementation through a carbon market mechanism, (2) indirect implementation through residents and enterprises, and (3) the use of relevant policies to influence the carbon market directly [55–59].

Table 2. Governments impacts on carbon price.

Transmission Mechanism	Measure
Direct effect to carbon markets	Price limit Supervision Carbon reserve
Indirect effect to enterprises	Quota allocation Tax and subsidy Mandatory measures Banking and borrowing
Indirect effect to residents	Fiscal measures and emissions reduction educations

Furthermore, other factors influence the price of carbon such as the influence of the energy market, financial market, and weather conditions (Table 3) [54,60,61].

Table 3. Markets and factors effective on carbon price.

Factor	Mechanism
Energy market	Enterprises' choice of energy use
Financial market	Stock indexes and enterprises' production type and level
Carbon market	Carbon future and option market
Weather condition	Consumer demand, enterprise production, energy price

Cap-and-trade systems in building decarbonization have some potential drawbacks that need to be carefully considered. One of the key concerns is the likely regressive influence on building owners and tenants, as the cost of emission allowances or permits could be passed down to consumers, leading to increased energy costs and potentially affecting lower-income households more significantly [60,61].

Administrative complexity is another issue, as implementing and managing a cap-and-trade system for the building sector requires accurate monitoring and reporting of building emissions, which can be difficult given the diverse range of building types and energy consumption patterns [60]. Furthermore, setting the appropriate emission caps can be complex, as it requires a delicate balance between ambitious emission reduction goals and the realistic capabilities of building owners and the industry [53].

There is also a risk of emission leakage, where some building activities could move to regions or areas with less stringent emission caps or regulations, potentially leading to a shift in the location of emissions rather than actual reductions. Additionally, the price volatility of emission allowances can impact the economic viability of building decarbonization projects, as unpredictable allowance prices may affect the cost effectiveness of emission reduction efforts. Ensuring social equity is crucial, as cap-and-trade systems might disproportionately affect vulnerable communities if allowances lead to increased energy costs for consumers. Lastly, there is a need for careful monitoring and enforcement to avoid potential loopholes or non-compliance with the cap-and-trade regulations, ensuring the system's effectiveness in achieving emission reduction targets [53,60].

To overcome these challenges, policymakers need to design cap-and-trade systems that consider the specific characteristics of the building sector and carefully calibrate emission caps to incentivize sustainable practices while avoiding undue economic burdens on building owners and tenants. Social safety nets and targeted support may be necessary to address potential equity issues. A well-designed cap-and-trade system can complement other policy measures, such as financial incentives and building codes, to create a comprehensive and effective approach to building decarbonization.

3.2.3. Carbon Offsetting

Carbon offsetting allows entities to compensate for their emissions by investing in alternatives that reduce or remove GHG emissions elsewhere. These projects can include alternative energy installations, reforestation or afforestation initiatives, energy efficiency programs, or GHG capture from landfills. By purchasing carbon offsets, entities can claim the reduction in emissions achieved by the offset projects as their own, effectively neutralizing a portion or all of their emissions. Carbon offsetting enables entities to take responsibility for their emissions while supporting sustainable projects that contribute to emission reductions globally.

Carbon offsetting projects are key in the fight against climate change, but not all initiatives have been successful in achieving their intended emission reductions. Several challenges have been encountered by some projects, leading to their failure or limited effectiveness. One common issue is proving additionality, which refers to demonstrating that the emission reductions or removals generated by the project would not have occurred without financial support from the offset market. The lack of robust monitoring and verification processes has also been a stumbling block, making it difficult to accurately measure and verify emission reductions in some cases [62,63].

Additionally, some carbon offset projects face concerns about the permanence of the carbon storage they rely on. For instance, afforestation or reforestation projects can be at risk of reversal due to forest fires, pests, or land-use changes, raising questions about the long-term effectiveness of these initiatives. Sustainable financing is another challenge, as some projects rely heavily on short-term funding or fluctuating carbon credit prices, making it difficult to ensure ongoing emission reductions [62].

Furthermore, certain projects have faced criticism for their potential negative social and environmental impacts. This includes situations where local communities are displaced, or biodiversity is unintentionally harmed by the offsetting activities. Double counting has also been a concern, where the same emission reductions are claimed by multiple parties, leading to an overestimation of the carbon offsetting impact [64].

Regulatory uncertainty, market price volatility, and issues of transparency and accountability have all contributed to the challenges faced by carbon offsetting projects. As the importance of carbon offsetting continues to grow, learning from past failures and addressing these challenges will be vital in ensuring the credibility and effectiveness of future projects. Implementing robust standards, rigorous verification processes, stakeholder engagement, and ongoing monitoring will be essential steps in enhancing the integrity and impact of carbon offset initiatives.

3.3. Subsidies and Incentives

Financial Incentives (FIs) refer to the financial assistance provided by governments or utility providers. These incentives, which may be subsidies, rebates, or disincentives, are typically contingent upon investors meeting specific energy efficiency requirements. Subsidies are provided to support energy upgrades and retrofits, allowing investors to carry out these improvements at a cost lower than the prevailing market price. Subsidies include grants, loans, or tax incentives. Loan incentives are used to facilitate the implementation of energy retrofits or the installation of energy-efficient equipment by offering favorable interest rates. By providing low-interest loans, a greater number of retrofits can become financially feasible compared to loans with higher interest rates. Grants are financial incentives that do not need to be repaid and are favored for their straightforwardness. They represent a significant amount of money that is typically provided by a government. A tax incentive refers to a monetary benefit in the form of a credit, deduction, or exemption from taxes that is granted if the building does not meet the required energy target but undergoes an energy upgrade. A rebate refers to the reimbursement of a portion or the entire amount spent on implementing energy upgrade measures. These rebates are commonly offered by utility providers when individuals or organizations purchase energy-efficient equipment. Financial disincentives are economic tools that discourage energy inefficiency by imposing negative consequences [41].

Overall, price-based or financial instruments, including subsidies, grants, rebates, and disincentives, are important tools to incentivize and promote the adoption of sustainable building practices. Figure 10 shows a comparison of cost effectiveness and environmental effectiveness from the social perspective. The findings on a societal level indicated that carbon taxes had low environmental and cost effectiveness, while capital subsidies, grants, and soft loans had high environmental effectiveness but low cost-effectiveness. Tax exemptions, on the other hand, demonstrated both high environmental and cost effectiveness among the FIs. Similar comparative analyses are needed to assess the perspectives of end users and the government [41,65].

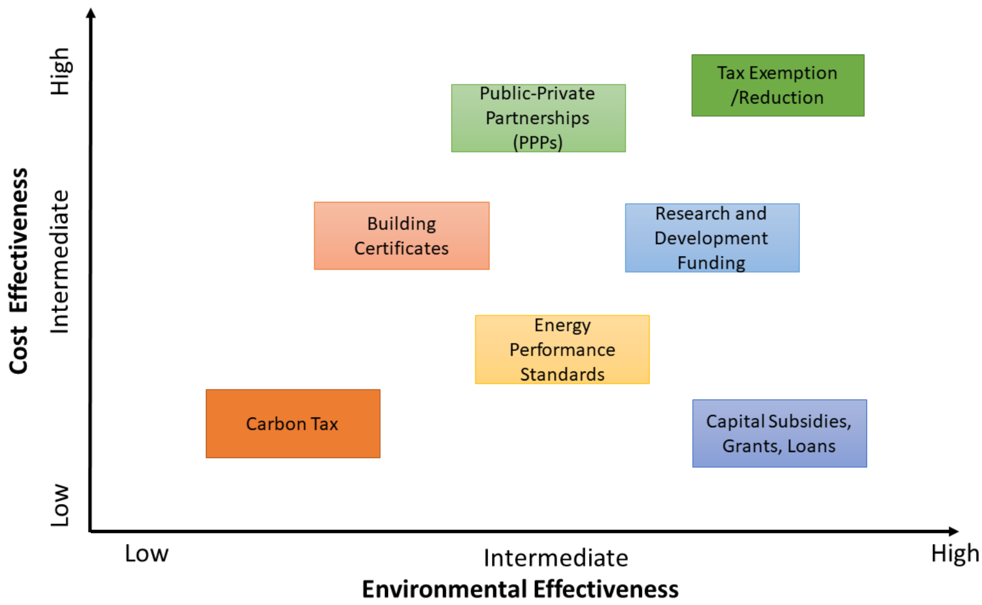

Figure 10. Environmental effectiveness versus cost effectiveness (map is generated using analyses found in the literature [41,43,54,65]).

3.4. Energy Performance Standards

Energy Performance Standards (EPSs) and guidelines for buildings establish the minimum energy-efficiency requirements for new construction and major renovations. These tools aim to improve the energy performance of buildings, reduce energy consumption, and lower GHG emissions. The specific themes of these standards can vary depending on the country or region where they are implemented. Table 4 shows some examples of well-known energy performance building standards from different parts of the world.

Table 4. Energy performance standards in different regions and countries.

Energy Performance Standards	Region
ASHRAE (American Society of Heating, Refrigerating, and Air-Conditioning Engineers)	The United States
NABERS (National Australian Built Environment Rating System)	Australia
Part L	The United Kingdom
GBES (Green Building Evaluation Standard)	China
NZEB (Nearly Zero-Energy Buildings) Standard	The European Union
Energiesprong	The Netherlands
Active House	Europe
Passive House	Europe

Each EPS differs in its ambition, international applicability, and focus on building energy efficiency. The Nearly Zero Energy Building (NZEB) standard is the most ambitious, aiming for almost zero net energy consumption and promoting renewable energy integration [66]. Part L (UK Building Regulations) and NABERS are also ambitious, requiring significant energy improvements in buildings to reduce carbon emissions [67].

Passive Houses prioritize energy efficiency and rely on insulation, air-tightness, and passive design strategies to minimize energy consumption for heating and cooling [68]. In contrast, Active Houses go beyond energy efficiency by emphasizing a holistic approach that also considers indoor comfort, air quality, and sustainability, often incorporating renewable energy sources and user-centric design elements. While both aim to reduce environmental impact, Active Houses place a stronger emphasis on creating a healthy and user-friendly living environment [69].

In terms of international applicability, ASHRAE is widely recognized and used primarily in the United States and Canada. NABERS is specific to Australia, Part L to the UK, Energiesprong to the Netherlands and GBES to China. NZEB, on the other hand, has gained international adoption, particularly in the European Union [70].

Each EPS system has a different focus on building energy efficiency. ASHRAE emphasizes thermal comfort, indoor air quality, and overall energy efficiency [71–76]. NABERS assesses operational energy efficiency, including water usage and waste management, for existing commercial buildings. Part L sets the energy performance standards for both new and existing buildings, targeting carbon emissions reduction. GBES evaluates various environmental aspects, including energy efficiency and indoor environment quality. NZEB aims to achieve nearly zero net energy consumption through stringent energy performance standards and renewable energy integration.

3.5. Building Certifications

Decarbonized building certifications are voluntary programs that assess and recognize buildings or construction projects for their environmental sustainability and energy efficiency. These certifications provide standardized criteria and performance benchmarks to guide the design, construction, operation, and maintenance of buildings in a more sustainable and environmentally responsible manner. They aim to reduce the environmental impact of buildings, improve occupant health and comfort, and promote resource efficiency.

Leadership in Energy and Environmental Design (LEED): LEED is one of the most recognized and widely used building certification programs worldwide. Developed by the U.S. Green Building Council (USGBC), LEED provides a framework for building owners and operators to design, construct, and operate sustainable buildings. It assesses various aspects of a building, including energy efficiency, water use, indoor environmental quality, materials selection, and site sustainability [77].

Building Research Establishment Environmental Assessment Method (BREEAM): BREEAM is a building certification developed in the United Kingdom by the Building Research Establishment (BRE). It evaluates buildings' environmental performance based on criteria related to energy and water use, materials, waste, pollution, and ecology [78].

Green Star: Green Star is an Australian green building certification program administered by the Green Building Council of Australia (GBCA). It assesses the sustainability attributes of buildings and communities, including the design, construction, and operational aspects [79].

Living Building Challenge (LBC): The Living Building Challenge is an ambitious green building certification program that goes beyond traditional sustainability measures. Developed by the International Living Future Institute (ILFI), it aims for buildings to become regenerative and give more than they take from the environment [80].

German Sustainable Building Council (DGNB): DGNB is a German certification system that evaluates the sustainability of buildings based on ecological, economic, and sociocultural criteria [81].

Estidama: Estidama is a sustainability initiative and building rating system developed for the United Arab Emirates (UAE), focusing on sustainability in the region's unique climate and cultural context [82].

Green Mark: Green Mark is a building rating system developed by the Building and Construction Authority (BCA) in Singapore. It evaluates buildings for their environmental impact and energy efficiency [83].

These certifications typically offer different levels of recognition, such as Certified, Silver, Gold, and Platinum (e.g., for LEED), based on the number of points or credits that a building project earns during the assessment process. They provide a road map for sustainable design and construction practices and encourage building owners and developers to incorporate green features and technologies into their projects.

Green building certifications have contributed significantly to raising awareness about sustainability in the construction industry and driving the adoption of environmentally friendly practices and technologies in buildings worldwide. Each certificate and standard has special criteria that are summarized in Table 5.

Table 5. Summary of criteria considered by different building decarbonization certifications.

Criterion	BREEAM	Green Star	LEED	DGNB	LBC	Green Mark
Management	✓	✓		✓		✓
Sustainable sites			✓	✓		✓
Indoor environmental quality		✓	✓	✓	✓	✓
Quality of service				✓		
Outdoor environment				✓	✓	✓
Energy	✓	✓	✓	✓	✓	✓
Materials	✓	✓		✓	✓	✓
Resources and material			✓	✓		
Transport	✓	✓		✓		
Water	✓	✓	✓	✓	✓	✓
Land use and ecology	✓	✓		✓	✓	
Emission or pollution	✓	✓	✓	✓	✓	✓
Innovation		✓	✓		✓	
Health and well-being	✓				✓	✓

3.6. Public–Private Partnerships (PPPs)

Public–private partnerships (PPPs) play a key role in addressing the challenges of adopting low-carbon technologies and practices. They bridge the gap between the public and private sectors, leveraging their respective strengths to advance sustainability. Public institutions contribute scientific research and policy support, while private companies drive innovation and scale up projects. By collaborating in PPPs, both sectors can accelerate the reduction in building GHG emissions. This collaboration enables efficient project management, knowledge sharing, and access to capital. Examples of PPP initiatives include decarbonized building standards, electric vehicle promotion, and recycling/waste-to-energy projects. Together, they set clear emission reduction goals and targets, contributing significantly to the fight against climate change [84,85].

3.7. Research and Development Funding

Investing in Research and Development (R&D) is a powerful strategy for driving innovation and accelerating the adoption of low-carbon practices in the building sector. Key aspects of R&D funding include researching new materials, promoting energy-efficient technologies, conducting life cycle assessments, utilizing digitalization and simulation, innovating processes, supporting startups, showcasing demonstration projects, facilitating knowledge sharing, and raising awareness. By strategically allocating R&D funding, societies can develop and implement innovative solutions that significantly contribute to mitigating climate change and promoting sustainable development.

4. Policy and Market Implications

4.1. Role of Government Incentives

As mitigating climate change becomes increasingly urgent, governments play a pivotal role in driving the adoption of sustainable practices within the built environment. This section examines various strategies and policies through which governments incentivize and facilitate the transition to low-carbon solutions. These interventions encompass financial incentives, regulatory frameworks, collaborative efforts, and market-based mechanisms, all aimed at reducing the embodied and operational carbon footprint of buildings [86–89].

- Governments can provide financial incentives, such as grants, subsidies, tax credits, or low-interest loans, to encourage organizations and individuals to invest in low-carbon solutions. These incentives can help offset the initial costs of adopting sustainable technologies, materials, or practices, making them more economically viable and attractive [86].
- Governments can allocate funding for research and development in low-carbon technologies, materials, and processes. By supporting innovation and technological advancements, governments can drive down costs, improve performance, and expand the availability of low-carbon solutions in the market. Governments can invest in capacity building programs and educational initiatives to raise awareness, encourage advocacy, and build knowledge about low-carbon solutions. This can include training programs, workshops, seminars, and educational campaigns targeted at professionals, businesses, and the general public. Enhanced knowledge and skills can facilitate the adoption of low-carbon practices and technologies [87].
- Government support for technological advancements significantly impacts the economic model of building decarbonization. For example, technology parks provide companies, particularly startups trying to commercialize innovative technologies, with advanced infrastructure and shared resources, reducing their capital expenditure. Additionally, government-funded programs for renewable energy, smart grid systems, and energy-efficient materials lower the costs of adopting low-carbon solutions. These initiatives not only accelerate sustainable building practices but also enhance economic viability by mitigating upfront costs and promoting long-term savings, driving progress in reducing the carbon footprint of buildings while stimulating economic growth [88].
- Furthermore, governments can establish regulations and standards that require or incentivize the use of low-carbon solutions. These can include setting carbon reduction targets, energy efficiency requirements, or building standards. Clear regulations

provide a level playing field, create market demand, and encourage organizations to prioritize low-carbon practices. Governments can drive demand for low-carbon solutions by incorporating sustainability criteria in public procurement processes. By giving preference to products, services, and projects involving building decarbonization, governments create a market pull effect and stimulate the adoption of sustainable practices across industries [87,89].

- Governments can facilitate collaboration among different stakeholders, including industry, academia, research institutions, and Non-Governmental Organizations (NGOs). By fostering partnerships, governments can create platforms for knowledge sharing, innovation, and the development of collaborative projects that focus on reducing carbon emissions. Also, governments can establish market-based mechanisms, such as carbon pricing or cap-and-trade systems, which assign a financial value to carbon emissions. These mechanisms create economic incentives for organizations to reduce their building GHG emissions and invest in low-carbon solutions to avoid or minimize financial liabilities [89].

4.2. Market Demand in Shaping the Low-Carbon Solutions

The market demand for low-carbon solutions encourages companies to invest in research and development to create innovative products and technologies. As consumers and businesses increasingly seek sustainable alternatives, companies strive to meet this demand by developing energy-efficient appliances, renewable energy systems, low-carbon materials, and other environmentally friendly products. The market demand for low-carbon solutions drives product innovation and pushes companies to find more sustainable and efficient ways of meeting customer needs [90].

As the market demand for low-carbon solutions grows, economies of scale can come into play. Increased production volumes and improved manufacturing processes often lead to cost reductions. For example, the increasing market for alternative energy technologies, such as photovoltaic panels and wind turbines, has driven their costs down significantly in recent years. The expanding market for low-carbon solutions can lead to cost-effective manufacturing methods, making them more accessible and affordable for consumers and businesses [91].

Market demand for low-carbon solutions influences supply chains by encouraging suppliers and manufacturers to adopt sustainable practices. Companies across the supply chain are motivated to reduce their own carbon footprints and seek out suppliers that provide low-carbon materials and components. This demand-driven shift encourages suppliers to prioritize sustainability, invest in more sustainable production processes, and enhance the environmental performance of their products. It creates a reinforcing effect throughout the supply chain, promoting the adoption of low-carbon practices at multiple stages [92].

Market demand for low-carbon solutions can influence policy and regulatory frameworks. Governments and regulatory bodies are more likely to introduce supportive policies and regulations when there is strong market demand for sustainable products and services. These policies can include renewable energy targets, energy efficiency standards, building system requirements, or emissions reduction goals. The alignment between market demand and policy support further accelerates the adoption of low-carbon solutions by providing a favorable environment for investment and innovation [93].

5. Case Studies

To understand the effect of economic landscape on building decarbonization, it is instructive to review a handful of real cases, in which the economic measures resulted in either a success or failure. In this section, this study reviews a few cases of each outcome.

5.1. Successful Case Studies

In this section, there are some case studies for economic incentives used to promote sustainable building practices (Table 6). These case studies demonstrate how economic incentives can effectively drive sustainable building practices by making decarbonization investments financially attractive for developers, building owners, and occupants. By leveraging economic incentives, governments and organizations can accelerate the adoption of environmentally friendly technologies and contribute to global efforts in building decarbonization and sustainability.

In California, the state government implemented an energy efficiency rebate program for residential and commercial buildings, which ran from 2010 to 2015. The program provided financial incentives, such as rebates and tax credits, to building owners and developers who implemented energy-efficient technologies and practices. This initiative encouraged the adoption of energy-saving measures, such as installing solar panels, upgrading insulation, and using energy-efficient appliances, leading to reduced energy consumption and lower utility bills for building occupants [94].

New York City introduced a property tax abatement program in 2008 for building owners who achieved certain energy efficiency standards. The program offered tax incentives to owners of buildings that met specific green building certifications, such as LEED or ENERGY STAR. By providing tax breaks to qualifying properties, the city aimed to encourage sustainable building practices and reduce GHG emissions, contributing to the city's climate action goals [95].

The Green Mark Scheme in Singapore has been promoting sustainable building practices since its inception in 2005. It is a green building-rating system that offers financial incentives and benefits to developers who construct environmentally friendly buildings. The scheme includes various levels of certification based on a building's sustainability performance. Developers of higher-rated buildings receive incentives, such as faster approvals, higher floor area ratios, and development charge rebates, thereby motivating them to incorporate sustainable design features and technologies [96].

Ontario, Canada, implemented a Feed-In Tariff (FIT) program from 2009 to 2016 to incentivize the adoption of renewable energy sources in buildings. The program provided guaranteed long-term contracts and premium rates for renewable electricity generation from sources such as solar, wind, and biomass. By offering stable and attractive prices for renewable electricity, the FIT program encouraged building owners to invest in on-site renewable energy systems, contributing to Ontario's clean energy goals [97].

Germany's Kreditanstalt für Wiederaufbau (KfW) offered financial incentives and 10-year low-interest loans for energy-efficient building retrofits and upgrades in the mid-1990s. The program provided funding for energy-saving measures, including insulation, heating system upgrades, and renewable energy installations. These incentives made energy-efficient renovations more financially viable for building owners and contributed significantly to Germany's efforts to reduce energy consumption and carbon emissions in the building sector [98].

In Colombia, the circular economy model in the construction industry for building decarbonization focuses on minimizing waste and maximizing resource efficiency through the reuse, recycling, and sustainable management of materials. This approach emphasizes the use of recycled building materials, modular construction techniques, and designing buildings for disassembly and reuse. In cities like Santiago de Cali, successful initiatives have demonstrated how construction waste can be repurposed into new projects, significantly reducing the carbon footprint. Government policies and incentives further support this shift, encouraging collaboration between public and private sectors to innovate and adopt circular practices. This model not only contributes to decarbonization efforts but also stimulates local economies, creates green jobs, and promotes sustainable urban development in Colombia [99].

Table 6. Summary of successful case studies on economic incentives for building decarbonization.

Program Name	Decarbonization Initiative	Country	Duration	Government Investment	Public Investment
Energy Efficiency Rebate Program	Rebates and tax credits for energy-efficient technologies and practices	USA (California)	2010–2015	State government funding	Building owners and developers
Property Tax Abatement Program	Tax incentives for buildings meeting energy efficiency standards (LEED, ENERGY STAR)	USA (New York)	2008–Ongoing	City government tax breaks	Building owners
Green Mark Scheme	Financial incentives for developers achieving high sustainability performance in buildings	Singapore	2005–Ongoing	Government incentives	Developers
Feed-In Tariff (FIT) Program	Guaranteed contracts and premium rates for renewable energy generation	Canada (Ontario)	2009–2016	Provincial government funding	Building owners and energy producers
Kreditanstalt für Wiederaufbau (KfW)	Financial incentives and low-interest loans for energy-efficient building retrofits and upgrades	Germany	1990s	Government-funded low-interest loans	Building owners
Circular Economy Model	Reuse, recycling, and sustainable management of building materials	Colombia	2012–Ongoing	Government policies and incentives	Construction industry stakeholders

5.2. Failed Case Studies

While economic incentives have generally been successful in promoting sustainable building practices, some initiatives have faced challenges and failed to achieve their intended outcomes. In this section, a few case studies of economic incentive programs are elaborated that did not yield the expected results (Table 7).

The Australian government launched the Home Insulation Program (HIP) in 2009 to stimulate the economy during the global financial crisis and promote energy efficiency in residential buildings. The program, which ran until 2010, provided subsidies to homeowners for installing insulation. However, rushed implementation and inadequate regulations led to issues such as improper installations, safety hazards, and poor-quality workmanship. Due to these failures and negative outcomes, the HIP was subsequently canceled [100].

Spain implemented a generous Feed-In Tariff (FIT) program in the early 2000s to promote solar photovoltaic installations, offering premium rates for renewable energy generation. However, rapid expansion and higher-than-expected uptake caused a significant budget overrun. In response, the government drastically reduced the feed-in tariff rates, causing financial losses for photovoltaic investors and a sudden decline in the solar industry. These abrupt policy changes led to a loss of investor confidence and hindered further deployment of photovoltaics in the country [101].

The UK Green Deal operated from 2013 to 2015 as an energy efficiency loan scheme aiming to finance improvements in homes. Homeowners could borrow money for insulation, heating systems, and renewable energy systems, with repayments made through energy bills. However, the scheme faced criticism for its complex structure, high-interest rates, and lack of attractive financial benefits, resulting in low uptake and limited impact. It was eventually discontinued due to these challenges [102].

The Canadian government launched the ecoENERGY Retrofit Program in 2007 to provide grants for energy efficiency upgrades in homes, such as insulation and HVAC systems. Initially successful, the program faced budget cuts and policy changes over its duration, leading to uncertainty and declining homeowner participation. Ultimately, the program was terminated in 2012, impacting the momentum of energy-efficient retrofits in residential buildings [103].

Table 7. Summary of failed case studies on economic incentives for building decarbonization.

Program Name	Decarbonization Initiative	Country	Duration	Government Investment	Public Investment
Home Insulation Program (HIP)	Subsidies for home insulation	Australia	2009–2010	Government subsidies	Homeowners
Feed-In Tariff (FIT) Program	Premium rates for solar photovoltaic installations	Spain	Early 2000s	Government subsidies	Renewable energy investors
Green Deal	Energy efficiency loans for home improvements	The UK	2013–2015	Government-backed loans	Homeowners
ecoENERGY Retrofit Program	Grants for energy efficiency upgrades	Canada	2007–2012	Government grants	Homeowners

6. Potential Barriers to Implementing Low-Carbon Solutions

One of the primary barriers is the perception that low-carbon solutions are more expensive than traditional alternatives. Upfront costs for sustainable materials, technologies, or construction practices can be higher, leading to concerns about the financial feasibility of implementation. However, it is essential to consider the long-term cost savings, operational efficiencies, and potential financial incentives associated with low-carbon solutions.

Many organizations and professionals may have limited awareness and understanding of low-carbon solutions and their benefits. This can lead to a lack of motivation or reluctance to adopt these approaches. Education and awareness campaigns are crucial to highlight the advantages of low-carbon solutions and provide information on the available technologies, best practices, and case studies.

The availability and accessibility of low-carbon materials and technologies can be a significant barrier. Some regions or industries may have limited options or suppliers for sustainable materials or energy-efficient technologies, making it challenging to implement low-carbon solutions. It is important to foster innovation, promote research and development, and create market demand to expand the availability of low-carbon options.

Regulatory frameworks and policies can either enable or hinder the adoption of low-carbon solutions. In some cases, outdated regulations or lack of supportive policies can create barriers to implementing sustainable practices. Governments and policymakers need to create an enabling environment by providing incentives, setting carbon reduction targets, and implementing supportive policies that encourage the adoption of low-carbon solutions.

The construction and manufacturing industries are often conservative and resistant to change, especially when it comes to adopting new technologies or practices. There may be concerns about the performance, reliability, or compatibility of low-carbon solutions with existing processes and systems. Overcoming resistance to change requires effective communication, showcasing successful case studies, and demonstrating the feasibility and benefits of low-carbon solutions.

Implementing low-carbon solutions often requires collaboration and coordination among multiple stakeholders, including designers, architects, engineers, suppliers, contractors, and clients. A lack of coordination and fragmented decision-making can impede progress. Engaging stakeholders early on, fostering collaboration, and establishing clear communication channels can help overcome this barrier.

Organizations may be hesitant to invest in low-carbon solutions if the return on investment is uncertain or if the payback period is perceived as too long. Economic analysis techniques, such as life cycle costing and net present value calculations, can help quantify the financial benefits and demonstrate the long-term value of low-carbon solutions.

Case studies from the United States, Germany, the UK, and Australia highlight common barriers to low-carbon initiatives. These include issues like lack of awareness, high upfront costs, regulatory complexities, and financing difficulties. Solutions involve targeted policies, financial incentives, public awareness campaigns, electricity grid modernization, policy stability, stakeholder collaboration, and engagement with end users to overcome these challenges and accelerate the adoption of sustainable practices [104–108].

7. Summary and Outlook

In summary, the review underscores the significance of economic landscape involving government programs and market forces in driving the adoption of sustainable building practices and reducing the carbon footprint of buildings. This study has also highlighted the economic potential of building decarbonization, demonstrating its capacity to create value while simultaneously addressing environmental concerns. The analysis reveals that price-based or financial tools, including subsidies, grants, rebates, and disincentives, are paramount in promoting sustainable building practices. Specifically, capital subsidies, grants, and soft loans exhibit high environmental effectiveness, making them powerful tools in transitioning to low-carbon buildings, despite their relatively low cost-effectiveness. Conversely, tax exemptions stand out as both environmentally and financially effective, highlighting their dual benefit. The effectiveness of these interventions, however, is context-dependent. Geographical, economical, and social factors significantly influence the success or failure of different economic instruments. For instance, carbon taxes, while theoretically sound, may face resistance or yield suboptimal results in regions with less stringent regulatory environments or lower public acceptance. In contrast, capital subsidies and grants are more universally applicable, offering substantial environmental benefits across various jurisdictions but requiring robust financial frameworks and governmental support to sustain. Moreover, the universality of these strategies is nuanced. While certain tools like tax exemptions can be broadly applied, others may require tailoring to local conditions. Policymakers must consider regional economic systems, social acceptance, and existing market dynamics to effectively implement these instruments. The study's findings suggests that a one-size-fits-all approach is not feasible; instead, a combination of strategies, adapted to specific contexts, is essential for maximizing both environmental and economic benefits. Overall, this research contributes to a deeper understanding of the economic dimensions of building decarbonization, thus offering valuable insights.

Looking to the future, several avenues warrant exploration. Firstly, further research should focus on the development of new technologies, materials, and construction practices that can substantially reduce building decarbonization and enhance sustainability. Additionally, advancements in life cycle assessment (LCA) methodologies and the creation of standardized benchmarks for measuring and comparing building decarbonization will be critical for more accurate assessments and informed decision-making. Understanding the effectiveness of policy instruments, evaluating economic feasibility, and examining the barriers to behavior change are essential areas for further investigation. Furthermore, in the context of real-world applications and case studies, ongoing research can provide valuable insights into the implementation of low-carbon solutions across various sectors and regions. Lastly, addressing geopolitical challenges and fostering international cooperation to balance economic growth with environmental responsibility remains a key challenge that requires extensive study and innovative solutions.

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Nomenclature

ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BCA	Building and Construction Authority
BRE	Building Research Establishment
BREEAM	Building Research Establishment Environmental Assessment Method
CBA	Cost–Benefit Analysis
CCER	Certified Carbon Emission Reductions
CO2e	Carbon Dioxide Equivalent
CSCC	Country-level of Social Cost of Carbon
DGNB	German Sustainable Building Council
EPS	Energy Performance Standards
ETS	Emissions Trading System
EU ETS	European Union Emissions Trading System
FI	Financial Incentives
FIT	Feed-In Tariff
GBC	Green Building Council
GBCA	Green Building Council of Australia
GBES	Green Building Evaluation System
GHG	Greenhouse Gas
HIP	Home Insulation Program
ILFI	International Living Future Institute
IRR	Internal Rate of Return
KfW	Kreditanstalt für Wiederaufbau
LBC	Living Building Challenge
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LEED	Leadership in Energy and Environmental Design
MAC	Marginal Abatement Cost
NABERS	National Australian Built Environment Rating System
NGOs	Non-Governmental Organizations
NPV	Net Present Value
NZEB	Net Zero Energy Building
PACE	Property Assessed Clean Energy
PPPs	Public–Private Partnerships
ROI	Return on Investment
SCC	Social Cost of Carbon
UAE	United Arab Emirates
UK	United Kingdom
USGBC	U.S. Green Building Council

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