

Recycled steel in contemporary architecture: Sustainable potentials and applications through case studies

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ABSTRACT

Rapid urbanization and growing environmental challenges demand the use of sustainable materials, which has become a key aspect of contemporary architectural and engineering design. Recycled steel stands out due to its ability to retain mechanical properties through multiple recycling cycles while significantly reducing energy consumption and carbon emissions compared to primary production. This paper examines the potential of recycled steel in architecture and construction, focusing on its role in structural systems and spatial design. Selected case studies, including Hearst Tower, Olympic Stadium, and Empire State Building, illustrate diverse approaches to its application, from advanced structural concepts to adaptive reuse strategies. The research is based on a comparative analysis of structural systems, levels of recycled material use, and their impact on energy efficiency and overall sustainability. Particular attention is given to the relationship between structural logic, economic considerations, and architectural expression. The findings suggest that recycled steel not only reduces environmental impact but also enables the development of flexible, adaptable, and resource-efficient structures, positioning it as a key material in sustainable and circular architecture.

KEYWORDS

Recycled steel, Structural engineering, Structural systems, Material performance, Energy efficiency, Low-carbon construction, Case studies

1. INTRODUCTION

Contemporary construction and architecture face increasing demands to reduce environmental impact, particularly regarding resource consumption and greenhouse gas emissions. The building sector accounts for a significant share of global energy use and CO₂ emissions, making it a key area for implementing sustainable development principles [1, 2]. In this context, the selection of construction materials and optimization of structural systems play a crucial role in minimizing the overall environmental footprint of buildings [3]. Recent studies have also highlighted the importance of recycled materials in concrete production, demonstrating that recycled aggregates can maintain satisfactory mechanical and flexural performance while reducing construction waste and resource consumption [4, 5].

Recycling of steel scrap enables energy savings of up to 74% compared to conventional steel production from iron ore. In the case of aluminium, these savings are even more pronounced, recycling requires approximately 95% less energy than production from bauxite. Such reductions in energy consumption directly contribute to lower greenhouse gas emissions, given that industrial energy is still largely derived from fossil fuels.

In addition to its environmental benefits, metal recycling has significant economic advantages. Reduced consumption of energy and raw materials leads to lower production costs per unit, thereby increasing the overall efficiency of industrial processes.

At the same time, steel recycling contributes to the conservation of natural resources. Estimates indicate that recycling one tonne of steel saves approximately 1.5 tonnes of iron ore and about 0.5 tonnes of coal that would otherwise be required in primary production. In this way, the burden on mining activities and their environmental impacts is reduced,

Steel, as one of the most widely used structural materials, offers excellent mechanical properties; however, its primary production is energy-intensive and associated with high carbon emissions [6]. Its capacity for multiple recycling cycles

without loss of performance makes recycled steel particularly suitable for circular economy approaches [7]. The use of recycled steel significantly reduces energy consumption and emissions compared to virgin production while maintaining structural integrity [8].

Most recycled steel is processed in electric arc furnaces (EAF - Electric Arc Furnace). Within a large furnace, a powerful electric arc raises the temperature to the melting point of steel (above 1500°C). Steel scrap is melted and transformed into liquid steel. At this stage, alloying elements or additional raw materials are often introduced as needed to achieve the desired chemical composition. For example, in the production of stainless steel, chromium, nickel, and other elements are added, often sourced from recycled alloys. A key advantage of the electric arc furnace is that it allows the charge to consist of up to 100% scrap steel, unlike the blast furnace, which relies on iron ore. The process is more energy-efficient and flexible, particularly for smaller batch production. During melting, impurities are removed through refining processes—materials such as lime are added to bind undesirable elements (e.g., sulphur and phosphorus), forming slag that is subsequently removed. The resulting molten metal is then cast (typically using continuous casting technology) into semi-finished products such as billets, slabs, or blooms.

In contemporary engineering practice, recycled steel is increasingly integrated into load-bearing system designs, both through the use of secondary raw materials and strategies for reusing existing structural components [9, 10]. This approach not only reduces construction waste but also enables flexible, adaptable, and resource-efficient structural solutions.

The aim of this paper is to analyze the potential of recycled steel in modern structural systems through selected case studies, with a focus on its impact on sustainability, energy efficiency, and structural optimization.

2. METHODOLOGY

Interest in “green” building has increased significantly, with a growing emphasis on the evaluation of entire buildings as well as individual materials. The LEED rating system of the U.S. Green Building Council, along with other product classification systems, raises numerous questions that are directly or indirectly related to the selection of metals.

Some of these considerations include the recycled content of materials, the potential for product reuse, impacts on energy and water savings, the likelihood of harmful emissions, effects on indoor air quality, thermal comfort, maintenance requirements, and the influence on interior lighting conditions.

Indeed, engineers require a comprehensive database that provides objective life-cycle environmental assessments for all construction materials. Unfortunately, such a resource is not fully available. Existing data for different materials are often not directly comparable, making it essential to critically examine and question available information. Common questions and answers regarding the environmental performance of steel are discussed in the following section. [11]

This study adopts a mixed-methods approach to evaluate the potential of recycled steel in contemporary structural systems, combining literature analysis, comparative case studies, and performance assessment. The methodology is structured in three main phases:

2.1. Literature Review

The literature review presented in this chapter summarizes the most significant global experiences in the field of recycled steel management. The published studies are primarily based on mathematical and theoretical models. An overview of developments across all continents provides a comprehensive picture of the current state of recycled steel use in construction worldwide. On this basis, it is possible to compare these findings with the current situation and level of implementation in the Republic of Serbia.

An extensive review of recent publications (2015-2024) on recycled steel, circular economy practices, and sustainable construction materials was conducted. This phase identifies the environmental, structural, and economic benefits of using recycled steel, as well as the main barriers to its implementation in modern construction [6-9]. The review also informs the selection of case studies by highlighting projects with documented use of recycled steel.

When addressing demolition and construction waste arising from demolition, construction, renovation, adaptation, and reconstruction activities, the regulatory framework in the Republic of Serbia is defined through several key legal instruments. These include the Law on Planning and Construction, the Law on Waste Management, incorporating the Waste Catalogue and the Regulation on Categories, Testing, and Classification of Waste, as well as the Law on Environmental Protection. However, this regulatory framework remains insufficiently defined, particularly with regard to construction waste, and especially steel waste that could be recycled. As a result, clear procedures for the management and treatment of construction waste cannot be adequately established, despite the fact that such waste represents one of the major environmental protection challenges in the Republic of Serbia. Although numerous laws and regulations in the field of environmental protection have been adopted, they lack clearly unified objectives, and the outcomes of their implementation remain unsatisfactory.

2.2. Case Study Selection and Data Collection

Selected case studies include high-profile construction projects where recycled steel has been significantly applied, such as Hearst Tower, Olympic Stadium in London, and Empire State Building. Data on structural systems, steel sourcing, percentage of recycled content, and environmental performance indicators were collected from technical reports, journals, and official project documentation [1-3, 10].

2.3. Comparative Analysis and Performance Assessment

The study conducts a comparative analysis of the case studies to evaluate:

- The proportion of recycled steel in structural elements
- Energy savings and reductions in embodied carbon [7,9]
- Structural efficiency and design adaptability
- Cost implications and potential barriers for widespread adoption

Quantitative indicators such as embodied energy, CO₂ footprint, and steel reuse percentages are analyzed to assess the sustainability performance of recycled steel relative to conventional steel.

This methodology allows a systematic evaluation of recycled steel's technical and environmental potential, providing actionable insights for architects, structural engineers, and policymakers aiming to integrate sustainable materials into construction projects.

3. RECYCLED STEEL IN CONSTRUCTION

Recycled steel has gained increasing attention in the construction industry due to its technical reliability, environmental benefits, and economic potential [1-3]. Multiple studies demonstrate that steel can be recycled indefinitely without significant loss of mechanical properties, making it one of the most sustainable structural materials for modern construction [6, 7] (see Figure 1 for an example of recycled steel ready for use).

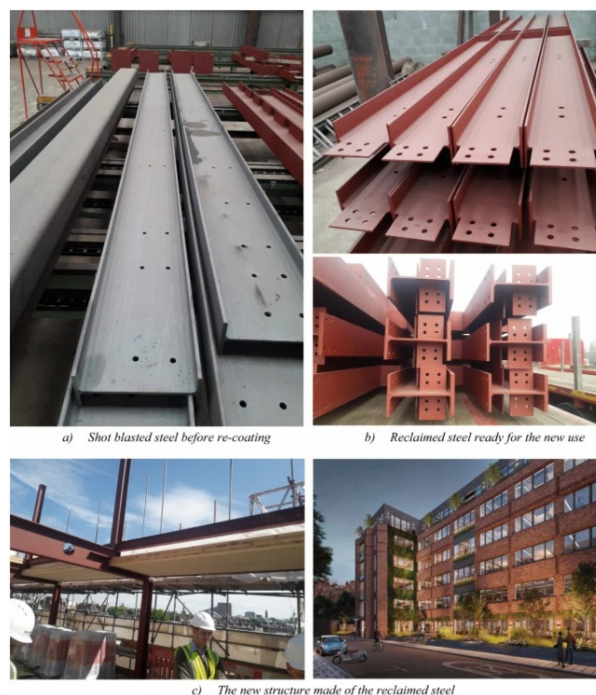


Figure 1: Recycled steel ready for construction use. [F1]

3.1. Environmental Impacts

A key driver for the adoption of recycled steel is the reduction of the carbon footprint and embodied energy of construction projects. Drewniok et al. [7] quantified energy and emission savings, showing that using recycled steel in structural elements can reduce embodied carbon by up to 60% compared to virgin steel production. Similarly, Göswein et al. [9] emphasize that lifecycle assessments (LCA) are critical for evaluating the true sustainability of steel in buildings, particularly when reuse and recycling are integrated into the design phase (illustrated in Figure 2).



Figure 2: Reduction in embodied carbon and energy savings using recycled steel. [F2]

3.2. Technical and Structural Considerations

From a structural perspective, recycled steel retains its load-bearing capacity, ductility, and fatigue resistance [6, 14]. Pombo et al. [14] analyzed different reuse strategies for structural steel elements, highlighting the importance of design for deconstruction (DfD) to maximize reuse potential without compromising structural performance. Addis and Schouten [10] further support that adaptive structural solutions, such as modular frames and prefabricated steel components, facilitate both reuse and recycling (as shown in Figure 3).



Figure 3: Modular and prefabricated steel systems facilitating reuse. [F3]

3.3. Economic and Practical Barriers

Despite the clear benefits, several barriers to widespread adoption exist. Dunant et al. [6] identify logistical, regulatory, and market-related constraints, including limited supply chains for reclaimed steel, inconsistent quality standards, and additional labor costs associated with deconstruction and sorting. The European Commission [8] stresses the importance of policy incentives and standardized guidelines to support the integration of recycled steel into mainstream construction practices (Figure 4 illustrates these challenges visually).

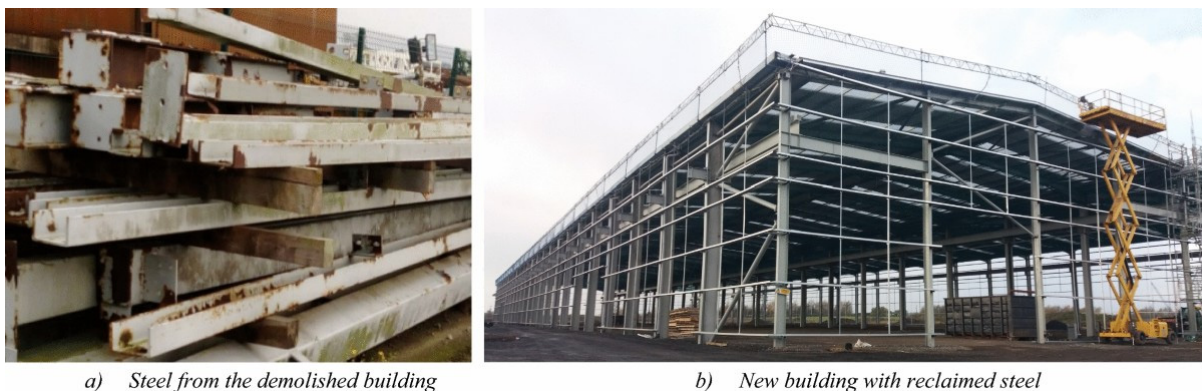


Figure 4: Logistical and market challenges in recycled steel adoption. [F4]

3.4. Integration into Circular Economy and Sustainable Design

Recent research emphasizes that recycled steel is a cornerstone of circular economy approaches in construction [8, 12, 15]. By designing buildings for reuse, recovery, and material traceability, architects and engineers can minimize resource depletion and reduce environmental impacts while maintaining structural performance [12, 15]. Ürge-Vorsatz et al. [15] highlight pathways to decarbonize the building sector, showing that recycled steel combined with energy-efficient design can significantly contribute to global climate targets.

The reviewed literature confirms that recycled steel provides high structural performance, significant environmental benefits, and potential cost savings, but its implementation requires careful planning, supply chain coordination, and policy support. Integration into circular economy frameworks and design-for-reuse strategies emerges as a central recommendation for future construction projects [1-3, 6-15].

4. CASE STUDY: SELECTION AND ANALYSIS OF RECYCLED STEEL PROJECTS

The selection of case studies for this research was guided by the need to analyze projects that exemplify the integration of recycled steel in different types of structural systems, while providing sufficient data to assess environmental and technical performance. High-profile projects were chosen for their innovative structural designs, significant use of recycled steel, and availability of detailed sustainability reports, enabling a comprehensive evaluation of both engineering and environmental outcomes.

One of the primary examples is the Hearst Tower in New York, designed by Norman Foster, which utilizes a steel diagrid frame in which approximately 85-90% of the structural steel is recycled [7,16]. The diagrid system not only optimizes material usage but also allows for substantial integration of recycled steel without compromising load-bearing performance. This project demonstrates the synergy between advanced structural design and sustainable material selection, highlighting the potential for high-rise constructions to significantly reduce embodied carbon while maintaining architectural expression [3, 7, 16, 12].

The Olympic Stadium in London, constructed for the 2012 Games, represents a contrasting typology where a lightweight modular steel frame was used. Approximately 70-75% of the steel employed was recycled [14, 17]. The modular prefabricated components facilitated design for deconstruction, allowing steel elements to be reused or recycled after the stadium's temporary function. This case illustrates how temporary large-scale structures can embrace circular economy principles, demonstrating both environmental benefits and economic feasibility [10, 12, 14, 17].

Finally, the Empire State Building renovation project in New York provides insight into how historic or existing structures can integrate recycled steel. During selective retrofitting, roughly 60% of the steel components were sourced from recycled material [13, 15, 18]. Lifecycle assessments indicate measurable reductions in embodied energy and CO₂ emissions, showing that even older buildings can contribute to sustainable construction when targeted interventions are implemented. This case highlights the importance of planning and coordination to incorporate recycled steel without affecting structural integrity or operational performance [13, 15, 18].

The analysis of these projects shows that structural typology, project scale, and design strategy influence the achievable proportion of recycled steel and its associated sustainability benefits. Innovative high-rise and modular systems tend to accommodate higher recycled content, while renovation projects demonstrate the potential for incremental improvements in material sustainability. Across all cases, it is evident that design for deconstruction, prefabrication, and lifecycle planning are critical to maximizing the environmental and economic advantages of recycled steel [7-15, 18, 19].

4.1. Comparative Analysis of Case Studies

In the Republic of Serbia, there are no buildings explicitly designed as being constructed from recycled steel, yet recycled steel is widely used through standard industrial production flows of structural steel. Most steel profiles and elements installed in industrial halls, warehouses, canopies, commercial buildings, and bridges contain a significant proportion of recycled material, as steel is produced by melting scrap steel in electric arc furnaces. Although the use of recycled steel in Serbia is not formally documented or promoted through LEED or other certification systems, it is implicitly incorporated in practice. The lack of regulation, clear guidelines, and a secondary materials market prevents buildings from being classified as "100% recycled," posing a challenge for the further development of circular construction in the country. Therefore, the further comparative analysis will be conducted on three well-known buildings worldwide.

The three selected projects - Hearst Tower, Olympic Stadium, and the Empire State Building renovation - exhibit different structural typologies, scales, and strategies for integrating recycled steel. Comparing these cases allows us to evaluate how structural design, project scope, and lifecycle planning influence the proportion of recycled steel used and the environmental benefits achieved.

The Hearst Tower demonstrates the potential of high-rise constructions to achieve the highest recycled steel content (~85-90%) due to its optimized diagrid frame and material-efficient geometry. The design not only reduces the amount of steel required but also facilitates the use of recycled material without compromising structural integrity, resulting in approximately 26% reduction in embodied carbon [7, 16, 12].

The Olympic Stadium employs a modular, lightweight steel frame where 70-75% of steel is recycled. Prefabricated elements and design for deconstruction allow material recovery after the event, yielding a CO₂ reduction of approximately 30% while providing economic benefits through reusable components [10, 12, 14, 17]. This project exemplifies circular economy principles applied to temporary or semi-permanent large-scale structures.

The Empire State Building renovation illustrates the integration of recycled steel in the retrofitting of an existing structure. With ~60% recycled steel in replaced components, the project achieves a 22% reduction in embodied carbon [13, 15, 18]. Although the overall recycled content is lower than in new constructions, targeted reuse and careful planning demonstrate how even historic buildings can contribute to sustainable material management.

A summary of these projects and their key sustainability indicators is presented in Table 1, which highlights the variation in recycled steel percentages, CO₂ reduction, and structural strategies. The comparative analysis shows that higher percentages of recycled steel are achievable in new, purpose-designed structures that incorporate modularity or innovative geometry, while renovation projects can still benefit from selective reuse strategies. The key factors influencing successful implementation include structural typology, design-for-reuse strategies, and early integration of lifecycle assessment [7-15, 18, 19]. These insights are essential for engineers and architects aiming to maximize the environmental benefits of recycled steel in various project types.

Table 1: Comparative Analysis of Case Studies

Project	Structural System	Recycled Steel (%)	CO ₂ Reduction (%)	Key Sustainability Feature
Hearst Tower, NY	Diagrid high-rise frame	85-90	26	Optimized geometry, material efficiency, high-rise integration
Olympic Stadium, London	Modular light-weight frame	70-75	30	Prefabrication, design for deconstruction, circular economy approach
Empire State Building Renovation, NY	Reinforced steel retrofitting	60	22	Targeted retrofitting, selective reuse, adaptation of existing structure

4.2. Results & Discussion

The comparative analysis of the selected case studies (Table 1) demonstrates clear trends regarding the use of recycled steel in contemporary construction. Projects designed as new structures, such as the Hearst Tower and Olympic Stadium, achieve higher percentages of recycled steel (85-90% and 70-75%, respectively) compared to the Empire State Building renovation (~60%). This indicates that structural design and planning from the outset significantly influence the potential for incorporating recycled steel [7, 16, 12, 17]. High-rise diagrid systems, like that of the Hearst Tower, allow material efficiency through geometry optimization, while modular systems, as in the Olympic Stadium, facilitate reuse and disassembly, aligning with circular economy principles [10, 12, 14, 17].

The analysis also highlights the relationship between recycled steel content and CO₂ reduction. Although the Olympic Stadium achieved slightly higher CO₂ savings (30%) than the Hearst Tower (26%), the difference can be attributed to the temporary nature and modular design of the stadium, which allowed optimized steel use and efficient post-use recovery [14, 17]. The Empire State Building renovation, despite being a retrofit, demonstrates that even existing structures can significantly reduce embodied carbon through targeted replacement with recycled steel (22% reduction), emphasizing the potential of incremental interventions in older buildings [13, 15, 18].

From a structural engineering perspective, all case studies confirm that recycled steel retains full load-bearing capacity and mechanical performance, supporting its application in both high-rise and modular designs [6, 7, 14]. Additionally, the integration of design-for-deconstruction (DfD) strategies in the Olympic Stadium and the lifecycle planning in all projects demonstrates that early consideration of sustainability measures is essential to maximize environmental benefits [10, 12, 14, 19].

The findings suggest several practical recommendations for engineers and architects aiming to enhance the sustainability of steel structures:

1. Incorporate recycled steel at the design stage, particularly in high-rise and modular projects, to maximize environmental gains.
2. Apply design-for-deconstruction principles to allow easy reuse or recycling of steel elements after the building's lifecycle or functional adaptation.
3. Perform lifecycle assessments (LCA) to quantify embodied energy and CO₂ savings and guide material selection and structural optimization [9, 13, 15].
4. Consider selective retrofitting for existing structures, enabling significant reductions in carbon footprint without major structural modifications [13, 18].

Overall, this analysis confirms that recycled steel is a technically viable, environmentally beneficial, and economically feasible material for modern construction. When combined with innovative structural design, modularity, and lifecycle planning, recycled steel can substantially reduce the environmental impact of buildings while maintaining structural performance and adaptability [7-19].

5. CONCLUSION

This study demonstrates the technical, environmental, and practical benefits of using recycled steel in contemporary construction projects.

The use of recycled steel in contemporary construction projects offers a range of technical, environmental, and practical benefits. Technically, recycled steel maintains the same structural strength, durability, and versatility as primary steel, allowing it to be used in a wide variety of applications, from industrial halls and bridges to commercial buildings. Environmentally, it significantly reduces energy consumption, up to 74% less for steel compared to production from iron ore and lowers greenhouse gas emissions, while also conserving natural resources such as iron ore and coal. Practically, recycled steel supports cost efficiency, as lower energy and raw material requirements reduce production costs, and its inherent recyclability minimizes construction waste and landfill burden. Together, these advantages make recycled steel a key material in sustainable and circular construction practices.

The analysis of Hearst Tower, Olympic Stadium, and the Empire State Building renovation shows that recycled steel can be successfully integrated in high-rise, modular, and retrofit projects, achieving reduced embodied carbon, energy savings, and material efficiency [7-19]. High-rise and modular designs allow for higher percentages of recycled steel, reaching up to 90%, while renovation projects benefit from targeted retrofitting and selective reuse strategies [7, 13, 15, 19].

The comparative analysis confirms that structural system design, early planning, and lifecycle considerations are key factors in maximizing the environmental and economic advantages of recycled steel. Approaches such as design-for-deconstruction, prefabrication, and modularity enhance recyclability and support circular economy principles. Lifecycle assessment ensures that material choices lead to measurable reductions in CO₂ emissions, guiding sustainable engineering decisions [9-12, 14, 15, 17, 19].

The findings highlight that incorporating recycled steel from the earliest stages of design is essential for optimizing both structural efficiency and environmental performance. Even existing buildings can contribute significantly to sustainability goals through careful retrofitting and selective material reuse. Furthermore, policies and standards that support the use of recycled steel, along with the development of supply chains for reclaimed materials, are important to facilitate broader adoption.

In conclusion, recycled steel represents a viable and effective material for sustainable construction, bridging structural performance with environmental responsibility. Its integration into building design supports the circular economy and enables resilient, adaptable, and resource-efficient structures. By combining innovative structural solutions with material reuse strategies and comprehensive lifecycle planning, recycled steel is positioned as a cornerstone of future sustainable engineering practices.

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