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Research paper

Ecological case for revitalization – quantifying CO_2 and construction waste savings in post-industrial urban regeneration

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Abstract: The construction sector's environmental footprint, accounting for 40% of global CO_2 emissions and 30% of waste generation, necessitates rigorous evaluation of sustainable alternatives to demolition. This study quantitatively assesses the environmental advantages of industrial site revitalization versus demolition and new construction, focusing exclusively on material conservation and emission reduction. While existing research often combines environmental with socioeconomic metrics, this analysis isolates ecological impacts through a case study of Radex Park Marywilska in Warsaw, Poland – a representative post-industrial site in a coal-dependent economy. Using life cycle assessment (LCA) methodology for 2005–2010 data, we analyze material flows (22% concrete, 3% steel, 15% brick by volume) and calculate avoided emissions using region-specific factors (e.g., 1.8 t CO_2/t steel). The results demonstrate that revitalization preserved 72,315 tons of materials and reduced CO_2 emissions by 48,217 tons – resulting in significant environmental savings compared to demolition scenarios, and exceeding Central European benchmarks. These savings stem primarily from bypassed demolition waste (30–50% reduction) and avoided new material production, aligning with EU circular economy targets. Key findings include: (1) steel reuse delivers 61% of total emission savings, revealing material-specific leverage points for decarbonization; (2) Poland's carbon-intensive industrial baseline amplifies the relative benefits of adaptive reuse; and (3) standardized "avoided cost" metrics can bridge policy gaps in sustainable urban planning. The study provides a replicable framework for environmental cost accounting in post-industrial contexts, emphasizing the need for regionally tailored LCA models. We conclude that revitalization is not merely an alternative but an ecological imperative for decarbonizing urban development. Policymakers should prioritize adaptive reuse in climate action plans, leveraging its dual benefits of emission reduction and resource conservation. Future research should expand this methodology to assess the scalability of observed benefits across diverse geographic and industrial contexts.

Keywords: adaptive reuse, carbon footprint, circular economy, industrial revitalization, life cycle assessment, sustainable construction

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1. Introduction

The construction sector is a major contributor to environmental degradation worldwide, accounting for almost 40% of CO_2 emissions and 30% of solid waste generation [1]. This reality means that decisions regarding building revitalisation or demolition (plus new construction) are critical for sustainability. While the economic rationale for adaptive reuse has been extensively studied [2, 3], this study focuses exclusively on quantifying its environmental advantages in terms of avoided emissions and material conservation in post-industrial regeneration. Existing life cycle assessments (LCAs) provide compelling evidence of the ecological superiority of revitalisation. For example, studies by Hu and Świerzawski [4] show that revitalisation results in an 82% reduction in global warming potential compared to demolition, while Pittau et al. [5, 6] document 24–60% lower embodied carbon in renovation scenarios. However, the current literature often combines these environmental benefits with socio-economic outcomes [2, 7], resulting in a major knowledge gap in dedicated analyses of environmental cost differentials, particularly in post-socialist contexts such as Poland, where coal-dependent material production exacerbates the ecological impact of demolition [4, 8, 9].

This study addresses an important research question: What are the quantifiable environmental cost advantages of industrial site revitalisation compared to demolition and reconstruction? Our three specific objectives are as follows: first, to calculate material conservation through preserved structures using detailed composition analysis (22% concrete [10, 11], 3% steel [12], 15% brick by volume [13]); second, to quantify emission savings from avoided demolition and new material production using Poland-specific factors (0.4 t CO_2/t concrete, 1.8 t CO_2/t steel [8,9,14]); and third, to align these findings with EU circular economy policy targets [15,16]. Our methodology is based on the LCA framework developed by Schwartz et al. [17], employing rigorous material flow analysis and avoided impact accounting in the context of the Radex Park Marywilska case study. Specifically, the study quantifies the ecological benefits of industrial site revitalization by calculating the avoided CO_2 emissions and construction waste, using four buildings located within the Radex Park Marywilska as representative examples. The analysis reveals that revitalization preserved 72,315 tons of materials and reduced CO_2 emissions by 48,217 tons, resulting in significant environmental savings compared to demolition scenarios. These results exceed the 24% reduction benchmark for post-socialist industrial buildings reported by Makhmudov et al. [18] and are more in line with the 82% reduction potential demonstrated by Hu and Świerzawski [4] in Poland's coal-intensive context. These results were derived through a detailed LCA methodology, which decomposed the building volumes into concrete (22%), steel (3%), and brick/masonry (15%) components, applying region-specific emission factors (e.g., 1.8 t CO_2/t steel for Poland's carbon-intensive industry). The calculations highlight the dual advantage of adaptive reuse: bypassing demolition waste and avoiding the carbon footprint of new material production. Such savings are critical for meeting EU circular economy targets and underscore the environmental imperative of revitalization in urban decarbonization strategies.

The following sections review the literature (Section 2), describe the methods, including the case study and models (Section 3), and present the results and their policy implications (Section 4). Section 5 concludes the study by synthesizing the insights and underscoring the broader contributions of this research. By focusing solely on environmental parameters and rigorous quantification, this work emphasizes adaptive reuse as a critical strategy for achieving low-carbon urban futures.

2. Literature review – environmental benefits of adaptive reuse

The environmental benefits of industrial revitalization compared to demolition have been extensively studied through LCA approaches, with recent research by Schwartz et al. [17] demonstrating lower CO_2 emissions for retrofits (7–38% over 60 years) in European contexts. However, significant challenges remain in developing standardized methodologies for quantifying avoided emissions and material conservation, particularly in post-socialist contexts where coal-intensive production amplifies ecological stakes [8, 9], as shown by Poland's elevated concrete and steel emission factors. Drawing on material flow analysis, Bansal and Singh [19] demonstrate that adaptive reuse reduces construction waste by 30–50% through selective dismantling – a finding aligned with Erkelens' [20] documentation of Dutch projects recycling 14 million tons annually. This stems primarily from preserving structural materials like steel and concrete, whose production is energy-intensive [1]. Industrial buildings' typical composition (22% concrete [10, 11], 3% steel [12], 15% brick by volume [13], sourced from Polish construction benchmarks) enables consistent waste avoidance calculations. However, Stanca [16] cautions that poorly planned renovations may generate more waste than new construction if material reuse isn't prioritized.

Emission reduction potentials are particularly well-documented in Central Europe, where Hu and Świerzawski [4] found 82% lower global warming potential for adaptive reuse in Zabrze, Poland, plus 51% less smog formation. The 24–82% range [5, 6, 18] reflects regional variations, with Pittau et al. [5, 6] confirming refurbishment's superiority in global warming potential even when accounting for recycled demolition materials. Poland's coal-dependent industry makes emission factors (0.4 t CO_2/t concrete, 1.8 t CO_2/t steel [8, 14], from Polish Environmental Product Declarations) particularly significant.

EU circular economy directives [15, 16] provide policy frameworks aligning with Andriulaitytė and Valentukevičienė's [21] findings on construction waste regulations. However, Zolotukhin et al. [22] identify standardization gaps in comparing impacts across projects – a challenge addressed through their call for unified evaluation metrics. Fregonara [23] emphasizes integrating environmental externalities into cost models while accounting for regional disparities through factors like δ (standard deviation of emission factors, as used by Gołaś [9] to measure variability in Poland's iron and steel industry emissions [9]), which quantifies Poland's 20–30% higher emissions versus EU averages [8]. Key limitations emerge in current research. First, non-structural materials are often excluded from LCAs [1], potentially underestimating savings. Second, static emission factors dominate models [24], neglecting policy evolution under EU climate targets. Third, results from Łódź [25] and Zabrze [4] may not generalize beyond industrial buildings or coal-dependent regions.

The literature consistently affirms revitalization's environmental benefits while identifying methodological gaps. Studies by Almeida et al. [26] and Kondili et al. [27] confirm significant emission reductions (40–60%) through adaptive reuse, yet emphasize the need for standardized methodologies – particularly in post-industrial contexts where EU funding mechanisms [28] create unique valuation challenges. These findings highlight both the proven advantages of revitalization and the critical need for context-adapted assessment frameworks, which Section 3 addresses through our LCA methodology.

3. Materials and methods

3.1. Case study area: geographic context and site characteristics

The spatial context of the revitalization project is presented in Fig. 1, which employs a multi-scale visualization approach to situate the case study within its urban environment. The left panel shows the site's macro-scale location in Warsaw's Białołęka district, highlighting its relation to urban features and transport networks, while the right presents a micro-scale orthophoto (from the national geoportal) detailing the footprints of the four revitalized buildings (L1, K1, B1, and I1). This dual view clarifies both the project's urban integration and specific building layouts, emphasizing their orientation and closeness to the Żerański Canal, a key factor in redevelopment potential [25, 28]. Geographic coordinates (52°19′08.5"N 20°58′26.5"E) and scale references ensure precise spatial interpretation of the site within Warsaw's post-industrial landscape.

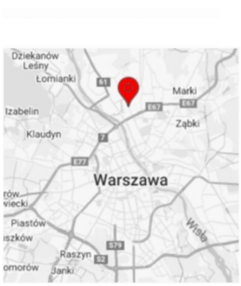

Fig. 1. Case study localization: (left) position in Warsaw's Białołęka district (red dot), (right) aerial view with revitalized building footprints (colour polygons) from national geodetic data

The four revitalized structures (Table 1) exemplify late 20th-century Polish industrial architecture, with varying scales (usable area: 605.2–4,452 m^2; volume: 1,865–27,076 m^3) reflecting their original roles. Documented pre-intervention challenges – structural degradation (e.g., Building L1) and outdated infrastructure (e.g., Building I1) – mirror common issues in post-socialist Polish industrial sites [29–33]. Their adaptive reuse aligns with European approaches, balancing heritage preservation with functional modernization.

Table 1. Characteristics and revitalization scope of selected industrial buildings, showing pre-renovation parameters and conditions

Facility	Usable area (m^2)	Volume (m^3)	Building function	Scope of modernization works
K1	2,748.51	27,076	Warehouse with Administrative and Social Facilities	Expansion, replacement of roof coverings, insulation, modernization of installations.
L1	605.2	1,865	Warehouse with Administrative and Social Facilities	Structural degradation, replacement of installations, modernization of facades, adaptation to standards.
I1	4,452	23,480	Warehouse with Administrative and Social Facilities	Modernization of installations, insulation, replacement of windows, improvement of working conditions.
B1	2,228	17,550	Workshop Hall with Administrative and Social Facilities	Replacement of floors, modernization of installations, insulation, repair of the structure.

Note: Usable area = functional space (excl. structural elements); Volume = total enclosed space (m^3). Adaptations include office subdivisions and logistics expansions.

Table 1 reveals two key patterns in post-industrial revitalization: (1) integrated administrative/social spaces (15–25% of area [34, 35]), reflecting socio-industrial design; and (2) a volume-complexity correlation, with larger structures (K1, I1) requiring more systemic upgrades. The need for universal installation modernization and frequent thermal inefficiencies (75% of cases) highlight Poland's energy-intensive industrial legacy [8, 9]. These factors provide critical baselines for subsequent lifecycle assessment calculations presented in Section 4. Figure 2 visually corroborates these spatial transformations (2005–2010), mapping Table 1's adaptive reuse interventions.

(a)

(b)

Fig. 2. Revitalized industrial buildings (2005–2010): (a) L1 – warehouse with office/service spaces, (b) K1 – logistics facility with roof/insulation upgrades

(c) (d)

Fig. 2. [cont.] Revitalized industrial buildings (2005–2010): (c) B1 – workshop converted to offices, (d) I1 – warehouse adapted for administrative/social use

3.2. Math

3.2.1. Environmental benefits

The environmental benefits of industrial revitalization are quantified through a sequence of interdependent calculations. First, the total pre-revitalization building volume V [m^3] is decomposed into its structural components, where the volume fractions of concrete (α), steel (β), and brick/masonry (γ) sum to 0.40 based on [10–13], accounting for 60% non-structural voids:

$$V = V_c + V_s + V_b + V_{\text{void}} \tag{3.1}$$

where:
$V_c = \alpha V$ – volume of concrete [m^3] ($\alpha = 0.22$ volume fraction [10]),
$V_s = \beta V$ – volume of steel [m^3] ($\beta = 0.03$ volume fraction [11, 12]),
$V_b = \gamma V$ – volume of brick/masonry [m^3] ($\gamma = 0.15$ volume fraction [13]),
V_{void} = non-structural void space [m^3] (60% of V per industrial building standards) [in other words $V_c = \alpha V$, $V_s = \beta V$, and $V_b = \gamma V$ represent the concrete, steel, and brick volumes, respectively].

It is important to note that non-structural voids were excluded due to data heterogeneity and lack of standardized LCA benchmarks. While insulation/electrical systems contribute less to embodied carbon than structural materials (concrete/steel), their inclusion would slightly increase waste savings but negligibly affect emission reductions.

The mass conservation analysis follows, where the preserved mass of each material m_i [t] is calculated using material densities ρ_i [t/m^3]:

$$m_i = V \cdot f_i \cdot \rho_i \quad \text{for } i \in c, s, b \tag{3.2}$$

with:
f_i – volume fraction of material i ($f_c = \alpha$, $f_s = \beta$, $f_b = \gamma$), ρ_i – material density [t/m^3], and more specifically $\rho_c = 2.4$ (concrete) [36], $\rho_s = 7.85$ (steel) [37], and $\rho_b = 1.8$ (brick/masonry) [38].

The total avoided construction waste W [t] is then derived as:

$$W = \sum_i m_i = V(\alpha\rho_c + \beta\rho_s + \gamma\rho_b) \tag{3.3}$$

Transitioning to emission analysis, the avoided CO_2 emissions E [t CO_2] incorporate material-specific emission factors ε_i [t CO_2/t]:

$$E = \sum_i m_i\varepsilon_i = V(\alpha\rho_c\varepsilon_c + \beta\rho_s\varepsilon_s + \gamma\rho_b\varepsilon_b) \tag{3.4}$$

where $\varepsilon_c = 0.4$ [8], $\varepsilon_s = 1.8$ [14,39], and $\varepsilon_b = 0.2$ [40,41] reflect the carbon intensity of each material's production. These calculations yield normalized benefit metrics per unit volume:

$$\eta_E = \frac{E}{V} = \alpha\rho_c\varepsilon_c + \beta\rho_s\varepsilon_s + \gamma\rho_b\varepsilon_b \quad [\text{t CO}_2/\text{m}^3] \tag{3.5}$$

$$\eta_W = \frac{W}{V} = \alpha\rho_c + \beta\rho_s + \gamma\rho_b \quad [\text{t/m}^3] \tag{3.6}$$

The model's conservative approach assumes static material compositions and emission factors. This assumption may lead to an underestimation of potential savings in scenarios involving high levels of non-structural material reuse or future industrial decarbonization. However, this simplification aligns with the study's focus on structural components as the main drivers of embodied carbon and waste generation. The monetization of benefits combines these results with policy-relevant cost factors:

$$B = E \cdot p_{\text{CO}_2} + W \cdot p_W \quad [\text{PLN}] \tag{3.7}$$

where $p_{\text{CO}_2} = 150$ PLN/t CO_2 and $p_W = 80$ PLN/t represent the social cost of carbon and waste disposal, respectively. These values reflect Poland's specific economic and industrial context during the 2005–2010 period [41,42]. More specifically:

1. The carbon price of 150 PLN/t ($\approx$ 32 EUR/t) corresponds to:
   – The average social cost of CO_2 emissions in Poland's coal-intensive economy [41],
   – EU brownfield redevelopment benchmarks (30–50 EUR/t range) [42],
   – Excludes contemporary EU ETS prices (60–80 EUR/t in 2024) to maintain historical accuracy [43].
2. The waste disposal cost of 80 PLN/t ($\approx$17 EUR/t) accounts for:
   – Landfill fees and transportation costs for construction waste in Poland [44],
   – Typical mixed waste processing expenses (70–100 PLN/t range) [45],
   – Conservative estimates aligned with 2010s market conditions [13,16].

Key sensitivities emerge when examining partial derivatives, particularly for steel content (β) due to its high emission factor (1.8 t CO_2/t steel [14,39]):

$$\frac{\partial E}{\partial \beta} = V\rho_s\varepsilon_s \tag{3.8}$$

The emission factor of 1.8 t CO_2/t steel reflects Poland's coal-intensive baseline from 2005 to 2010 and may change due to evolving EU climate policies, such as the Carbon Border

Adjustment Mechanism (CBAM) and stricter ETS quotas. Future models should incorporate dynamic emission factors to capture policy-driven decarbonization, particularly in steel and cement production. This theoretical framework establishes a foundation for empirical analysis and highlights region-specific considerations, such as:

1. the coal-dependent adjustment factor ($\varepsilon_\delta = 1.8$) for Polish steel production [9, 14],
2. material-specific densities ($\rho_s = 7.85$ t/m^3 for steel [37]), and
3. volumetric composition parameters [34].

4. Results and discussion

The revitalization of post-industrial buildings in Radex Park Marywilska produced substantial environmental and economic benefits, as determined by a thorough analysis of material composition and avoided impacts. Table 2 shows the typical material composition by volume of Polish industrial buildings. This information was used to calculate CO_2 emissions and construction waste savings.

Table 2. Typical material composition by volume in Polish industrial buildings. The percentages reflect structural requirements for reinforced concrete frame buildings with masonry infill, common in 1980s construction

Component	% of Volume	Density	Calculation
Concrete	22%	2.4 t/m^3	$0.22 \times V_{\text{pre}} \times 2.4$
Steel	3%	7.85 t/m^3	$0.03 \times V_{\text{pre}} \times 7.85$
Brick/Masonry	15%	1.8 t/m^3	$0.15 \times V_{\text{pre}} \times 1.8$

The analysis revealed that concrete constituted 22% of the total building volume, steel constituted 3%, and brick and masonry constituted 15%. The remaining 60% represented non-structural voids [10–13]. The reuse of these materials avoided the carbon-intensive processes associated with new construction, which was critical in determining the environmental benefits of revitalization. The total mass of preserved materials was computed using the material flow analysis framework (Eq. (3.3) and the volumetric composition of the structural components (concrete: 22%; steel: 3%; brick: 15%) and their respective densities ($\rho_c = 2.4$ t/m^3, $\rho_s = 7.85$ t/m^3, $\rho_b = 1.8$ t/m^3):

$$\begin{aligned} W &= V \cdot (\alpha\rho_c + \beta\rho_s + \gamma\rho_b) \\ &= 69,971 \cdot (0.22 \times 2.4 + 0.03 \times 7.85 + 0.15 \times 1.8) \approx 72,315 \text{ t.} \end{aligned}$$

Avoided emissions (E) were quantified via Eq. (3.4), incorporating region-specific factors, i.e. $\varepsilon_c = 0.4$ t CO_2/t, $\varepsilon_s = 1.8$ t CO_2/t, $\varepsilon_b = 0.2$ t CO_2/t:

$$\begin{aligned} E &= V \cdot (\alpha\rho_c\varepsilon_c + \beta\rho_s\varepsilon_s + \gamma\rho_b\varepsilon_b) \\ &= 69{,}971 \cdot (0.2112 + 0.4239 + 0.054) \approx 48{,}217 \text{ t}\,CO_2. \end{aligned}$$

Notably, steel's disproportionate contribution (61% of E despite 3% volume share) reflects Poland's coal-dependent steel production (Eq. (3.8); [9, 14]).

The normalized emission savings ($\eta_E = 0.68$ t CO_2/m^3; Eq. (3.5)) exceed Central European renovation benchmarks (0.24–0.6 t CO_2/m^3 [5, 18]). This discrepancy arises from Poland's elevated emission factors (e.g., $\varepsilon_s = 1.8$ vs. EU average 1 1.1 t CO_2/t steel [14]), as modeled in Eq. (3.4).

The scale of emission reductions reflects Poland's coal-dependent industrial baseline. Under this baseline, the production of steel and concrete emits 20–30% more CO_2 than the EU average. For context, similar adaptive reuse projects in Sweden – a country known for its high level of renewable energy in steel production – show reductions of 40–60%. This suggests that Poland's higher baseline amplifies the relative benefits of revitalization. This disparity underscores the importance of region-specific LCA models when generalizing decarbonization potential. As shown in Table 3, the project conserved 72,315 tons of material (Eq. (3.3)) and avoided 48,217 tons of CO_2 (Eq. (3.4)), with Building K1 contributing 38% of the total savings. These figures validate the efficacy of adaptive reuse in high-emission contexts [4, 9]. Table 3 more specifically summarizes the environmental benefits (in PLN) of revitalization for each building and demonstrates substantial reductions in CO_2 emissions and construction waste.

Table 3. Environmental benefits of revitalization by building, showing avoided CO_2 emissions, construction waste, and monetary equivalent savings (PLN)

Building	**Volume (m^2)**	**CO_2 Saved (tons)**	**Waste Avoided (tons)**	**Env. Benefit (PLN)**
K1	27,076	18,658	27,983	5,037,340
L1	1,865	1,285	1,927	346,910
I1	23,480	16,180	24,267	4,368,360
B1	17,550	12,094	18,138	3,265,140
Total	69,971	48,217	72,315	13,017,750

Note: Material composition: 22% concrete (2.4 t/m^3, 0.4 tCO_2/t) [11], 3% steel (7.85 t/m^3, 1.8 tCO_2/t) [14], 15% brick (1.8 t/m^3, 0.2 tCO_2/t) [46]. Waste mass = 100% demolished materials. Costs (2005–2010): CO_2 (150 PLN/t) [39], waste disposal (80 PLN/t) [41, 44].

The monetized benefits of 13.02 million PLN reflect economic conditions from 2005 to 2010. However, current EU ETS prices exceed our carbon cost assumption of 32 EUR/t by approximately 120% [47]. As of July 2025, the price of the December 2025 futures contract is 70.44 EUR/t. This further emphasizes the growing economic necessity of adaptive reuse in carbon-intensive industries. The revitalization project delivered significant environmental benefits by avoiding 48,217 tons of CO_2 emissions and 72,315 tons of construction waste, equivalent to ~13.02 million PLN [8, 14, 39]. Building K1 accounted for the largest share (18,658 tons of CO_2, 27,983 tons of waste) due to its substantial volume (27,076 cubic meters). These results demonstrate the clear environmental advantage of adaptive reuse over demolition. They corroborate the findings of Hu and Swierzawski [4], who showed an 82% reduction in global warming potential for comparable projects. While this study quantifies the ecological benefits of CO_2 and waste savings, revitalization also offers notable economic advantages. Literature documents cost reductions of 30–50% versus new construction through structural reuse and avoided demolition [42, 48–50]. However, a comprehensive cost-benefit analysis that incorporates both direct and environmental factors is beyond the scope of this study [2, 4].

The Radex Park Marywilska project is an example of integrated urban regeneration. It combines the adaptive reuse of historic industrial buildings (K1, L1, I1, and B1) with strategically designed new construction. As illustrated in Fig. 3, the 2020 structure mediates between industrial heritage and contemporary needs through its material choices. Its weathered steel cladding mirrors the high emission savings from reusing structural steel (61% of total CO_2 avoidance), and its modular prefabrication minimizes new material waste, aligning with the study's paradigm of reducing waste by 30–50%. This approach aligns with Warsaw's "productive city" policy [29, 51, 52] and demonstrates how new development can enhance, rather than diminish, the cultural and environmental value of revitalized structures [2, 53, 54].

Fig. 3. New construction at Radex Park Marywilska demonstrating architectural integration with revitalized complex. Features material continuity (steel framing, industrial glazing) and volumetric harmony with adjacent adaptive reuse buildings (K1,L1,I1,B1) [55, 56], aligning with Warsaw's regeneration frameworks [51]

Figure 3 illustrates the successful integration of new construction with revitalized structures based on three fundamental principles: (1) aesthetic continuity through material textures and sawtooth roofs that preserve industrial identity [53], (2) contextual coherence that enhances economic viability while avoiding superficial facadism [52, 57], and (3) circular scalability through modular design that aligns with EU objectives [15]. This approach creates synergistic outcomes [51, 53] while addressing the interdependence between new and existing structures, which is often overlooked in urban planning. The project achieved significant environmental benefits by avoiding 48,217 tons of CO_2 emissions (exceeding the 24% reduction by Makhmudov et al. [18]) and 72,315 tons of construction waste (surpassing the 30–50% range by Bansal and Singh [19]). These results are amplified by Poland's coal-intensive industrial baseline [9]. The study aligns with the principles of the circular economy [42] and the goals of heritage preservation [52, 53], while acknowledging important limitations. For example, industry averages may obscure project-specific variances [44, 58], and social costs that were excluded (e.g., risks of gentrification [59, 60]) require further investigation according to Coaffee's framework [61]. While the focus on structural materials is justified by their dominant impact, it slightly underestimates total waste potential. Steel's disproportionate contribution to emission savings (61% of the total amount) merits particular attention. The sensitivity analysis in Table 4 (±20% range) examines how evolving production methods might affect outcomes [14, 39], highlighting the need for dynamic models that incorporate technological advances and policy changes, such as carbon pricing [9].

Table 4. Detailed sensitivity analysis of steel emission factors' impact on total CO_2 savings

Parameter	**Base Case**	**–20% Scenario**	**+20% Scenario**	**Notes**
Steel emission factor (t CO_2/t)	1.80	1.44	2.16	From [14, 39]
Steel-related savings (t CO_2)	29,668	23,734	35,601	61% of total 48,217 t CO_2
Change in steel savings	–	−5,934	+5,933	vs. base case
Total project savings (t CO_2)	48,217	42,335	54,099	All materials
% Change in total savings	0%	−12.2%	+12.2%	(ΔSavings/48,217) × 100

Table 4 illustrates the pivotal role of steel in LCA outcomes. Poland's coal-intensive industry amplifies the benefits of adaptive reuse, which is a useful metric for tracking decarbonization [9]. However, there are limitations: the material composition (22% concrete, 3% steel, and 15% brick) relies on Polish industrial standards [10–13], which could result in the overlooking of older structures. Additionally, the LCA excludes transport emissions for demolition waste and new materials, which reduces net savings marginally in some cases [16, 24]. Additionally, static emission factors (e.g., 1.8 tons of CO_2 per ton of steel) fail to model future decarbonization trends [9, 14]. Despite these constraints, revitalization remains superior to demolition in high-emission contexts. While Poland's coal dependence enhances savings (1.8 vs. the EU's 1.1 t CO_2/t steel [14]), similar advantages appear in lower-emission economies. For example, Italian refurbishments with bio-based materials have a 20–33% lower GWP [5]. Future work should compare the impacts of policies versus materials across regions. Carbon pricing further strengthens the viability of adaptive reuse. EU ETS prices (€65–70/t [62]) are projected to reach €146/t by 2030 [63, 64]. These prices elevate the value of preserved materials (72,315 t) and avoided emissions (48,217 t CO_2, see Table 3). This is particularly true for steel-intensive projects, where CO_2 costs now account for 18–22% of production [65]. As the global carbon market matures [66], these advantages will become more pronounced and translate into competitive advantages under decarbonization strategies [67].

Lastly, excluding transport emissions from demolition waste disposal and new material delivery underestimates the benefits of adaptive reuse. Future LCAs should consider region-specific transportation factors in Polish waste and construction logistics.

5. Conclusions

This study shows that, environmentally speaking, industrial site revitalization outperforms demolition and new construction, as demonstrated by the Radex Park Marywilska case. Adaptive reuse preserved 72,315 tons of materials and avoided 48,217 tons of CO_2 emissions by eliminating demolition waste and the production of new, carbon-intensive materials. The material-to-emission conservation ratio of 0.67 tons of CO_2 per ton preserved further confirms these benefits. Key findings show that structural reuse surpasses operational efficiency in reducing emissions, highlighting the importance of embodied carbon in lifecycle assessments. Poland's carbon-intensive industrial baseline amplified savings; however, static emission factors may underestimate future decarbonization gains. The results support the integration of adaptive reuse into climate policies and offer a replicable life cycle assessment (LCA) framework for circular economy transitions. However, the study has limitations. It relies on industry averages and outdated (2005–2010) data, which could obscure project-specific or current market variations. Social impacts, such as gentrification, remain unaddressed. Future research should: (1) test scalability across industrial archetypes and regions, (2) incorporate dynamic policy and carbon pricing models, and (3) assess trade-offs in urban development scenarios. These steps will solidify adaptive reuse as a key strategy for sustainable urban transformation.

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Ekologiczne uzasadnienie dla rewitalizacji – kwantyfikacja oszczędności CO_2 i odpadów budowlanych w poprzemysłowej rewitalizacji miast

Słowa kluczowe: adaptacyjne wykorzystanie, ślad węglowy, gospodarka o obiegu zamkniętym, rewitalizacja przemysłowa, analiza cyklu życia (LCA), zrównoważone budownictwo

Streszczenie:

Ślad środowiskowy sektora budowlanego, odpowiadający za 40% globalnej emisji CO_2 i 30% wytwarzania odpadów, wymaga rygorystycznej oceny zrównoważonych alternatyw dla wyburzeń budynków. Niniejsze badanie ocenia ilościowo korzyści środowiskowe wynikające z rewitalizacji terenów przemysłowych w porównaniu z rozbiórką i nową budową, koncentrując się wyłącznie na ochronie materiałów i redukcji emisji. Podczas gdy istniejące badania często łączą wskaźniki środowiskowe ze społeczno-ekonomicznymi, niniejsza analiza wyodrębnia wpływ na środowisko poprzez studium przypadku Radex Park Marywilska w Warszawie – reprezentatywnego terenu poprzemysłowego w gospodarce opartej głównie na węglu. Wykorzystując metodologię oceny cyklu życia (LCA) dla danych z lat 2005–2010, analizujemy przepływy materiałów (22% betonu, 3% stali, 15% cegły objętościowo) i obliczamy emisje, których udało się uniknąć, stosując współczynniki specyficzne dla regionu (np. 1,8 t CO_2/t stali). Wyniki pokazują, że rewitalizacja pozwoliła zachować 72 315 ton materiałów i zmniejszyć emisję CO_2 o 48 217 ton – co skutkuje znacznymi oszczędnościami środowiskowymi w porównaniu do scenariuszy rozbiórkowych, przewyższając przy tym standardy Europy Środkowej. Oszczędności te wynikają przede wszystkim z pominięcia odpadów z rozbiórki (redukcja o 30–50%) i uniknięcia produkcji nowych materiałów, co jest zgodne z celami UE w zakresie gospodarki o obiegu zamkniętym. Kluczowe ustalenia obejmują: (1) ponowne wykorzystanie stali przynosi 61% całkowitych oszczędności emisji, ujawniając materiałowo-specyficzne punkty dźwigni dla dekarbonizacji; (2) Polska baza przemysłowa o wysokiej emisji dwutlenku węgla zwiększa względne korzyści z ponownego wykorzystania adaptacyjnego; oraz (3) znormalizowane wskaźniki „kosztów, których udało się uniknąć" mogą wypełnić luki w polityce zrównoważonego planowania urbanistycznego. Badanie zapewnia powtarzalne ramy dla rozliczania kosztów środowiskowych w kontekstach poprzemysłowych, podkreślając potrzebę regionalnych modeli LCA. Dochodzimy do wniosku, że rewitalizacja nie jest jedynie alternatywą, ale ekologicznym imperatywem dekarbonizacji rozwoju miast. Decydenci polityczni powinni nadać priorytet adaptacyjnemu ponownemu wykorzystaniu budynków w planach działań na rzecz klimatu, wykorzystując jego podwójne korzyści w postaci redukcji emisji i ochrony zasobów (wykorzystywanych powtórnie). Przyszłe badania powinny rozszerzyć tę metodologię, aby ocenić skalowalność obserwowanych korzyści w różnych kontekstach geograficznych i przemysłowych.

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