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Production margins: from industrial heritage to socio-ecological regeneration

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Abstract.

The contribution sets out a nexus-based framework for the adaptive reuse of industrial heritage, integrating Water, Energy, and Carbon (WEC) with "Degree of Conservation," Governance Intensity, and Multiscalarity. The model was applied to 15 international case studies, and an "Integrated Index" (0–9) was introduced to assess the degree of metabolic integration in relation to protection, scale of intervention, and institutional capacity. The findings indicate that the most robust configurations emerge at the district level, characterised by significant structural conservation and structured governance. The proposed framework offers a replicable systemic metric with the potential to guide post-industrial regeneration in the ecological transition in a comparable and transparent manner.

Keywords: water-energy-carbon nexus; heritage-oriented design; adaptive reuse; industrial heritage; multi-systemic assessment.

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Beyond the Conservation-Performance Dichotomy: Industrial Reuse in the Climate Transition

The adaptive reuse of industrial heritage currently represents one of the most relevant and complex fields within contemporary urban regeneration. Post-industrial landscapes constitute significant portions of urban fringes across diverse European and international contexts. These areas cannot be interpreted merely as residual productive sites; rather, they should be understood as stratified territorial systems endowed with historical, technological, identity-related, and landscape values (ICOMOS & TICCIH, 2011).

At the same time, the building and construction sector accounts for a substantial share of global greenhouse gas emissions, including both operational emissions and embodied emissions associated with materials (UNEP, 2022). In this context, the conservation and reuse of existing building stock assume a strategic role in reducing emissions and preserving embodied carbon stocks (Lim, 2025). Recent literature highlights that demolition and reconstruction often result in a higher climate impact than structural reuse, particularly during the first decades of the life cycle (Röck et al., 2020).

However, the ecological transition does not concern energy alone. Climate change intensifies hydraulic risks, increases the frequency of extreme events, and requires a reorganization of urban water cycles (IPCC, 2022). Within this framework, the integrated management of resources – water, energy, and embodied carbon – emerges as a central interpretative paradigm. The Water-Energy-Carbon (WEC) Nexus underscores the interdependencies among infrastructural systems and urban metabolic processes (Jing-Li et al., 2019; Duan, 2016), highlighting the need for integrated approaches.

Despite these theoretical advancements, a significant gap remains: Nexus literature rarely incorporates the conservation dimension of industrial heritage, while studies on adaptive reuse tend to address environmental components in a sectoral manner. This contribution positions itself at this intersection, proposing an operational framework capable of integrating Water, Energy, and Carbon dimensions with the conservation intensity of the intervention and governance aspects, thereby formalizing a replicable evaluation system applied to an international comparative sample.

Theoretical Framework: Industrial Heritage Conservation, Adaptive Reuse, and the Nexus Paradigm

Industrial heritage has been internationally recognized as a specific category within the broader field of heritage, characterized by distinct typological and value-based attributes. The Nizhny Tagil Charter for the Industrial Heritage (TICCIH, 2003) defines such assets as tangible and intangible testimonies of the productive and technological processes that have shaped modern societies. The Dublin Principles (ICOMOS & TICCIH, 2011) emphasize the importance of preserving authenticity, integrity, and legibility of industrial structures, promoting interventions that are compatible and reversible.

Conservation theory has progressively acknowledged adaptive reuse as a key instrument to ensure the long-term survival of heritage assets (Plevoets and Van Cleempoel, 2019). More recently, the debate has expanded to incorporate environmental and climatic dimensions into the evaluation of interventions. The conservation of existing structures entails the preservation of a significant amount of embodied carbon contained in building materials, thereby framing heritage protection as an implicit climate strategy.

In parallel, the Nexus paradigm has emerged as a theoretical framework for analyzing interdependencies among resources. Recent studies demonstrate that integrating water, energy, and climate systems enables the identification of synergies and the prevention of unintended consequences resulting from sectoral policies. However, these models are predominantly applied to contemporary infrastructure systems or newly planned urban developments, and only rarely to contexts characterized by high levels of historical stratification and conservation constraints.

Furthermore, urban governance literature highlights that the ecological transition requires institutional arrangements capable of coordinating diverse actors and monitoring performance over time (Bulkeley et al., 2014; Jordan et al., 2015). In industrial reuse contexts – often marked by public–private partnerships and a plurality of interests – governance cannot be regarded as a mere administrative backdrop, but rather as a structural component of sustainability.

This framework underscores the need for an integrated model that connects conservation, metabolic integration, and governance within a unified analytical perspective.

Research Gap and Research Objectives

A review of the literature reveals three principal gaps. First, studies on the energy efficiency of the built heritage predominantly focus on operational performance, often neglecting the water dimension and the carbon dimension in terms of embodied stock and life-cycle assessment. This limits the capacity of existing evaluations to account for systemic interdependencies. Second, while the Nexus paradigm provides a robust theoretical framework for analyzing the relationships among water, energy, and carbon, it rarely incorporates the degree of conservation intensity of the intervention. In industrial heritage contexts, existing morphology and regulatory protection frameworks profoundly condition the technical feasibility of energy and water solutions. The absence of an explicit variable measuring conservation intensity represents a significant theoretical gap. Third, governance is frequently treated as a qualitative contextual factor, but it is seldom formalized as a comparable and assessable dimension within environmental evaluation models.

Considering these gaps, the present research pursues the following objectives:

1. To integrate the Water–Energy–Carbon paradigm with the conservation dimension and governance within a systemic evaluation model.
2. To formalize a replicable scoring system based on an “Integrated Index” (0–9), “Degree of Conservation” (0–3), “Governance” (0–3), and “Multiscalarity” (0–2).
3. To apply this system to an international sample of case studies in order to identify recurring configurations and structurally favorable conditions.
4. To propose an operational framework applicable both for ex-post evaluation and as ex-ante decision-support.

This contribution thus aims to bridge the gap between conservation theory and the Nexus paradigm by offering a systemic metric capable of guiding the regeneration of industrial margins toward configurations that are both climatically coherent and culturally grounded.

Case Studies and Construction of the Comparative Model

The comparative analysis of case studies constitutes the empirical device through which the Water–Energy–Carbon paradigm is translated into a methodological structure applicable to the adaptive reuse of industrial heritage. Comparison was not conceived as a mere description of design strategies, but rather as the construction of an interpretative model capable of making explicit the relationships among resource management, conservation intensity, and governance arrangements. The sample of fifteen case studies was selected according to intentional criteria: documented industrial or infrastructural origin; significant permanence of original structures; advanced or completed stage of reuse intervention; availability of technical documentation; and the presence of at least one strategy attributable to the WEC paradigm. The geographical and regulatory diversity of the sample enables testing the robustness of the framework across different contexts.

The adopted methodology combines a qualitative descriptive matrix with a replicable ordinal coding system aimed at constructing synthetic indices. This approach avoids both interpretative impressionism and false numerical precision, maintaining appropriate granularity (0–3 and 0–2 scales) while ensuring methodological transparency.

The analysis is structured around six dimensions: Water, Energy, Carbon, Degree of Conservation, Governance, and Multiscalarity. The first three constitute the basis of the “Integrated Index” (INI = W + E + C; range 0–9), while the remaining dimensions operate as structural interpretative variables.

Water Dimension (W): Urban Water Cycle and Territorial Resilience

The Water dimension assesses the extent to which the project reorganizes the water cycle within the regenerated site, considering remediation processes, sustainable urban drainage systems (SUDS), blue–green infrastructure, and water reuse strategies. In industrial margins—often characterized by extensive soil sealing and land contamination—water management constitutes a structural component of climate resilience and ecological regeneration (Tab. 1). Literature on the WEC Nexus emphasizes that water management cannot be understood as an autonomous sector, but rather as an integral part of urban metabolic processes.

Energy Dimension (E): Demand Reduction and Local Production

The Energy dimension considers both the reduction of energy demand through interventions on building envelopes and systems, and on-site energy production from renewable sources. In industrial heritage contexts, energy integration must confront morphological and conservation constraints (Tab. 2). Literature on adaptive reuse and circular economy strategies in the built environment highlights that energy retrofitting measures must remain compatible with the conservation of material and cultural values.

Carbon Dimension (C): Embodied Stock and Life Cycle

The Carbon dimension integrates the preservation of embodied carbon stored within existing structures with potential strategies aimed at reducing both operational and embodied emissions. The conservation of industrial structures entails maintaining the existing carbon stock as a central component of decarbonization strategies in the built environment (Tab. 3).

“Degree of Conservation” (Co): Nature of the Conservation Intervention

The “Degree of Conservation” measures the intensity of the conservation approach adopted. In adaptive reuse processes, the extent of morphological transformation directly influences both the possibilities for energy integration and the embodied impact of newly introduced components. The distinction among integral, structural, and partial conservation enables the interpretation of trade-offs between heritage protection and environmental performance (Tab. 4).

Governance (Go): Decision-Making Structure and Monitoring
Governance represents the institutional dimension that conditions the continuity and effectiveness of environmental strategies (Tab. 5). Structured models—characterized by formalized partnerships, management plans, and monitoring systems—are associated with higher levels of systemic integration (Maziotis et al., 2024).

Multiscalarity (MS): Spatial Dimension of the Intervention
Multiscalarity assesses the spatial scale of the intervention, distinguishing between single-building projects and district-scale regeneration processes. Nexus literature highlights that many resource synergies emerge only beyond the building scale, when interventions can engage dynamics operating at the broader neighborhood or district level (Tab. 6).

Formalization of the Indicators
The evaluation of the dimensions outlined above is carried out through the definition of a composite index representing a synthetic measure of the degree of metabolic integration among the three environmental dimensions. It is expressed on an ordinal scale ranging from 0 to 9:

$$Integrated\ Index\ (INI)=W+E+C$$

The indicators CI (0–3), Co (0–3), and MS (0–2) function as complementary structural variables, enabling a multidimensional interpretation of systemic configurations.
The adoption of ordinal scales (0–3 and 0–2) ensures sufficient granularity without introducing artificial precision. The resulting system allows for transparent and replicable comparison, consistent with the theoretical framework of the Water–Energy–Carbon Nexus and with international principles for the conservation of industrial heritage. The comparative analysis makes it possible to identify the principal design strategies and conservation approaches adopted in the case studies (Tab. 7), thereby providing the empirical basis for subsequent evaluative formalization.

Integrated Comparative Analysis: Systemic Configurations and Interrelationships Among Indicators

The values attributed to the dimensions and structural variables outlined above are made explicit through the comparative scoring system illustrated in Figure 1, whose relational structure enables the calculation of the “Integrated Index” (INI).
The application of the model to the fifteen case studies transcends a purely descriptive level of analysis and enables the identification of recurring systemic configurations in the adaptive reuse of industrial heritage. The INI provides a synthetic measure of the degree of metabolic integration among water, energy, and carbon, whereas the Co, Go, and MS indices allow for the interpretation of the structural conditions within which such integration is achieved.

The distribution of INI values reveals a concentration between 4 and 7, indicating predominantly intermediate levels of integration across the sample. No intervention attains the theoretical maximum value (9), thereby confirming that the simultaneous and fully balanced integration of the three environmental dimensions constitutes a rare condition within actual regeneration processes. This outcome is consistent with the scientific literature on urban transformation within the WEC Nexus framework, which underscores the persistent sectoral fragmentation characterizing environmental strategies.

From an interpretative perspective, three principal typologies of approach can be identified. Cases with INI values ≤4 exhibit partial or sectoral integration, characterized by the predominance of one dimension over the others. Those with INI values between 5 and 6 demonstrate an intermediate balance. Cases with INI ≥7—although limited in number—display more balanced configurations, generally associated with district-scale interventions and structured governance arrangements.

The introduction of the "Degree of Conservation" (Co) prevents reductive interpretations according to which greater integration would necessarily imply greater physical transformation. In cases with Co = 3, characterized by integral or near-integral conservation, limitations are sometimes observed in the Energy dimension due to morphological constraints. However, when "Multiscalarity" (MS) = 2, such limitations can be compensated through the redistribution of energy infrastructure to less sensitive buildings. In these contexts, the scale of intervention emerges as a key variable in overcoming the apparent conflict between conservation and performance.

In cases with Co = 1 or 2, increased morphological flexibility facilitates technological integration, but may entail higher embodied emissions associated with newly introduced components. The combined analysis of INI and Co thus renders explicit the structural trade-offs between energy integration and conservation intensity, in line with the literature addressing the balance between heritage protection and sustainability in the built environment.

Multiscalarity is confirmed as a determining variable. Cases with MS = 2 display, on average, higher INI values and greater balance among W, E, and C. The synergies characteristic of the Nexus paradigm tend to manifest fully beyond the building scale, where it becomes possible to share energy infrastructure, coordinate water management, and calibrate conservation strategies in a differentiated manner. The district dimension aligns with the principles underlying climate-neutral city strategies, which identify the integrated urban scale as the most effective operational threshold for complex environmental strategies.

The Governance index (Go) also functions as an enabling variable. Cases with Go ≥2 are predominantly situated within the medium-to-high INI range, suggesting a correlation between decision-making capacity and systemic integration. Where formalized management plans and monitoring instruments are in place, environmental strategies tend to be more coherent and continuous; conversely, in cases with Go ≤1, such strategies remain episodic. Adaptive governance therefore assumes a central role in multisystemic transformation processes.

The combined reading of the parameters allows the identification of four recurring configurations: (i) water-driven, characterized by high W values and medium-to-high conservation intensity; (ii) carbon-retention, emphasizing structural conservation; (iii) multilevel integration, defined by INI ≥6, MS = 2, and Go ≥2; and (iv) capital-intensive landmark, characterized by high Energy values and variable degrees of conservation. These configurations do not constitute qualitative hierarchies, but rather systemic patterns that make visible different equilibria between heritage protection and metabolic integration.

In summary, the analysis demonstrates that environmental integration cannot be interpreted independently of conservation intensity, scale, and governance. The adopted index system does not generate a ranking; rather, it makes explicit the structural relationships that condition coherence between adaptive reuse and the ecological transition. The combined use of the “Integrated Index” (INI) and the structural variables Co, Go, and MS thus enables the overcoming of sectoral fragmentation and supports the interpretation of industrial heritage as a multilevel system in which metabolic integration, conservation, and institutional capacity interact dynamically.

Construction of the Nexus-Based Operational Framework for the Adaptive Reuse of Industrial Heritage

The comparative evidence presented in the tables demonstrates that the adaptive reuse of industrial heritage cannot be governed through sectoral instruments or linear evaluation models that separate conservation from environmental performance. In the analyzed cases, the effectiveness of WEC strategies consistently depends on the conservation intensity of the intervention, the scale of application, and the governance structure. The framework thus emerges from the need to simultaneously integrate the Nexus paradigm, heritage protection, and institutional capacity, enabling the comparison of alternative scenarios and making trade-offs explicit.

The model is grounded in four core principles: systemic integration of the WEC dimensions; explicit incorporation of the conservation variable as a structural parameter; recognition of multiscalarity as an enabling condition; and adaptive governance and monitoring as prerequisites for life-cycle robustness. The indices are not conceived as targets to be maximized, but as diagnostic instruments.

Conceptual Architecture

The “Integrated Index” (INI) is defined as the sum of the W, E, and C scores (0–3 each). It represents a synthetic measure of the degree of metabolic integration among water management, energy performance—including on-site renewable production—and carbon strategies related to the preservation of embodied stock and, where available, life-cycle assessment. Three structural variables complete the system:

- “Degree of Conservation” (Co) (0–3): the nature of the conservation intervention, ranging from predominantly transformative approaches to integral or reversible conservation;
- “Governance” (Go) (0–3): the institutional capacity to implement and monitor integrated strategies;
- “Multiscalarity” (MS) (0–2): the scale of the intervention, from single-building projects to integrated district-level regeneration.

While the INI expresses the level of environmental integration, the variables Co, Go, and MS condition its coherence and feasibility. From this perspective, sustainability in adaptive reuse does not coincide with the maximization of the INI; rather, it lies in achieving a balanced relationship among metabolic integration, heritage conservation, and managerial capacity.

Operational Evidence

The multisystemic analysis of the case studies outlined above makes it possible to identify evident contrasts in the adaptive reuse practices under consideration. Configurations characterized by higher INI values are predominantly observed at the district scale (MS = 2) and in the presence of structured governance arrangements (Go ≥ 2). Energy integration—including renewable energy production—proves more coherent when distributed across clusters of buildings, thereby avoiding invasive interventions on structures with higher heritage value.

Moreover, high values of the “Degree of Conservation” index (Co ≥ 2) do not automatically imply low environmental integration. Conservation can coexist with satisfactory WEC performance when supported by appropriate scale and governance structures, thereby overcoming the conventional opposition between heritage protection and energy performance and reframing it as an issue of spatial redistribution and systemic coordination.

Finally, governance emerges as a decisive factor in ensuring performance continuity. In the absence of formalized management arrangements and monitoring mechanisms, environmental strategies tend to remain episodic. The robustness of metabolic integration is therefore closely linked to institutional capacity.

Operational Procedure

The adopted methodological approach enables the definition of a framework for the integrated evaluation of adaptive reuse interventions in industrial heritage contexts, structured into four distinct phases. The first phase consists of a systemic site diagnosis, integrating assessment of conservation values, water-related criticalities, energy profile, potential for preservation of structural carbon stock, and stakeholder mapping.

The second phase involves the construction of alternative scenarios, differentiated not only by technical solutions but by overall configuration: distribution of technologies, degree of conservation, and governance model.

The third phase entails comparative evaluation through scoring, applying the W, E, and C dimensions alongside the structural variables Co, Go, and MS. The INI synthesizes environmental integration, while Co, Go, and MS clarify conservation coherence, intervention scale, and implementability of solutions. The resulting framework supports both ex-ante and ex-post assessments, providing a comparative analytical structure rather than an automatic hierarchy.

The fourth phase concerns scenario selection and the definition of a monitoring plan, establishing indicators consistent with the WEC dimensions and conservation requirements. Monitoring constitutes a structural component, necessary to ensure long-term verifiability.

Trade-Offs and Interpretative Thresholds

The framework renders explicit the most recurrent trade-offs: (i) energy integration versus morphological integrity; (ii) operational improvement versus increased embodied emissions; (iii) blue–green infrastructure versus maintenance management; and (iv) urban enhancement versus real estate pressures. These tensions are not eliminated but rendered analytically comparable.

Based on the empirical evidence, interpretative thresholds may be identified as analytical—rather than prescriptive—reference values: INI ≥ 6 indicates at least intermediate integration; Co ≥ 2 ensures significant conservation coherence; Go ≥ 2 reflects adequate managerial capacity; MS = 2 represents an enabling condition for redistributing technologies and mitigating conservation–performance conflicts.

Methodological Contribution

The framework contributes in three principal directions: it operationalizes the application of the WEC paradigm to industrial heritage; it explicitly integrates the conservation dimension into environmental evaluation; and it distinguishes between technical integration and institutional capacity, enabling more precise analysis.

The clarity of the adopted scales (0–3, 0–2, 0–9) and the scenario-based structure ensure replicability in both ex-post analytical applications and ex-ante decision-support processes.

In summary, the model translates comparative evidence into an analytical device capable of verifiably balancing metabolic integration, heritage conservation, and governance, thereby providing a methodological foundation for the systemic regeneration of disused industrial landscapes.

Discussion: Theoretical and Operational Implications of the Nexus-Based Framework

The introduction of an integrated evaluation system—based on the “Integrated Index” (INI, 0–9), “Degree of Conservation” (Co, 0–3), Governance (Go, 0–3), and Multiscalarity (MS, 0–2)—enables a systemic reinterpretation of the adaptive reuse of industrial heritage, overcoming the traditional dichotomy between conservation and technological innovation. By integrating the Nexus paradigm with conservation theory, the framework provides a comparable metric for post-industrial urban margins.

From Performance-Oriented Design to Metabolic Systems

Scholarship on the energy retrofitting of the built heritage has frequently prioritized the energy dimension. The comparative analysis presented here demonstrates, instead, that the sustainability of industrial reuse depends on the interaction among water management, energy performance, and climate-mitigation strategies. The Integrated Index (INI) renders visible the degree of integration across Water, Energy, and Carbon, while also indicating that such integration is not merely additive: high values in the Energy dimension do not compensate for deficits in the other dimensions.

Sustainability thus emerges as an equilibrium among interdependent components, consistent with the Nexus paradigm. The framework contributes to shifting attention from the individual building to an integrated territorial system, in which technological choices are evaluated in relation to conservation intensity, scale, and governance.

Conservation as a Structural Parameter

One of the key findings concerns the “Degree of Conservation” (Co). The case studies show that substantial structural conservation ($Co \geq 2$) can coexist with medium-to-high INI values when supported by appropriate multiscalar strategies and governance arrangements. Conservation therefore does not operate primarily as a constraint; rather, it becomes a structural parameter that guides the spatial distribution of environmental strategies.

In contexts characterized by high Co values, energy production can be redistributed at the district scale, preserving the integrity and legibility of buildings that are most sensitive to transformation. At the same time, the preservation of existing volumes functions as a climate-mitigation action by reducing embodied carbon emissions. Through the performance interrelations captured by the INI, the framework overcomes the opposition between conservation and the energy transition, reframing it as a question of systemic configuration.

Multiscalarity and Governance as Enabling Conditions

Multiscalarity emerges as a decisive variable. Cases with MS = 2 display greater balance among the WEC dimensions and higher INI values. Nexus-related synergies manifest most fully beyond the building scale, where shared energy infrastructures, coordinated water management, and differentiated conservation intensity across buildings become feasible.

Similarly, governance intensity affects life-cycle robustness. In cases with Co ≥ 2, the presence of management plans and monitoring mechanisms supports continuity and coherence of environmental strategies. The distinction between INI and Co enables an analytical separation between technical integration and institutional capacity, while acknowledging their interdependence: without structured governance, metabolic integration remains fragile.

Emerging Configurations and Theoretical Contribution

The combined use of the indices allows the identification of recurring configurations—water-driven, carbon-retention, multilevel integration, and capital-intensive landmark—which represent different equilibria between heritage protection and systemic integration. These interpretative patterns render visible structural trade-offs among operational efficiency, embodied emissions, and socio-economic pressures.

From a theoretical standpoint, the framework explicitly integrates the WEC paradigm with the conservation dimension, distinguishing between environmental integration (INI) and the structural conditions that shape it (Co, Go, MS). Methodologically, the use of ordinal scales ensures transparency and replicability in contexts characterized by heterogeneous data availability.

Some limitations remain, particularly the uneven availability of LCA data and the partially qualitative nature of certain governance indicators. Further research could strengthen the model’s quantitative dimension through comparative life-cycle analyses and simulation-based tools.

In summary, the adaptive reuse of industrial heritage emerges as a systemic process in which environmental integration, conservation, scale, and governance interact dynamically. The proposed framework provides an analytical structure capable of guiding complex decisions in a transparent and comparable manner, contributing to a redefinition of the relationship between industrial heritage and the ecological transition.

Conclusions: Toward a Systemic Metric for the Adaptive Reuse of Industrial Heritage

This contribution demonstrates that the adaptive reuse of industrial heritage cannot be interpreted either as a merely conservation-oriented operation or as a simple exercise in energy retrofitting. The comparative analysis of fifteen case studies—formalized through the Integrated Index (INI), Degree of Conservation (Co), Governance (Go), and Multiscalarity (MS)—shows that sustainability in post-industrial contexts constitutes a systemic property, grounded in the multisystemic interaction among performance, conservation, and institutional arrangements.

The integrated application of the Water–Energy–Carbon paradigm enables the reinterpretation of industrial heritage as an active infrastructure. The preservation of structural stock does not represent an obstacle to the climate transition; rather, it constitutes an implicit carbon resource to be accounted for and valorized. The Degree of Conservation thus emerges as a structural parameter that orients environmental strategies, moving beyond the interpretation of heritage protection as a residual constraint.

The Integrated Index is not proposed as a performance ranking, but as a diagnostic device capable of revealing imbalances among water management, energy integration, and climate-mitigation strategies. Its combined interpretation with Co, Go, and MS makes it possible to identify coherent configurations and to compare alternative scenarios transparently. The evidence indicates that more robust configurations tend to occur when at least intermediate environmental integration (INI ≥ 6), significant conservation intensity (Co ≥ 2), district-scale intervention (MS = 2), and structured governance (Go ≥ 2) converge. In such contexts, trade-offs between heritage protection and energy production can be managed through spatial redistribution of technologies and continuous monitoring.

The ecological transition in industrial margins thus emerges as a process requiring integrated planning at the scale of building clusters or districts, rather than isolated interventions on individual structures, thereby positioning multiscalarity as a structural condition of Nexus-based integration.

The contribution of the framework is threefold: (i) it explicitly integrates the conservation dimension into the Nexus paradigm; (ii) it proposes a replicable formalization based on transparent ordinal scales; and (iii) it provides a tool applicable both ex post and ex ante.

Nevertheless, certain methodological limitations remain. The uneven availability of LCA data constrains the precise quantification of carbon-related environmental impacts, while governance assessment relies predominantly on qualitative indicators. Future research may strengthen the model through comparative life-cycle analyses, dynamic energy simulations, and more analytically structured institutional metrics, thereby enhancing its quantitative robustness.

In conclusion, the adaptive reuse of industrial heritage may be interpreted as a privileged laboratory for the urban ecological transition. The proposed systemic metric integrates conservation, metabolic integration, and governance within a coherent analytical framework, offering both research and design practice a tool for guiding complex decisions in a transparent and comparable manner.

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Images

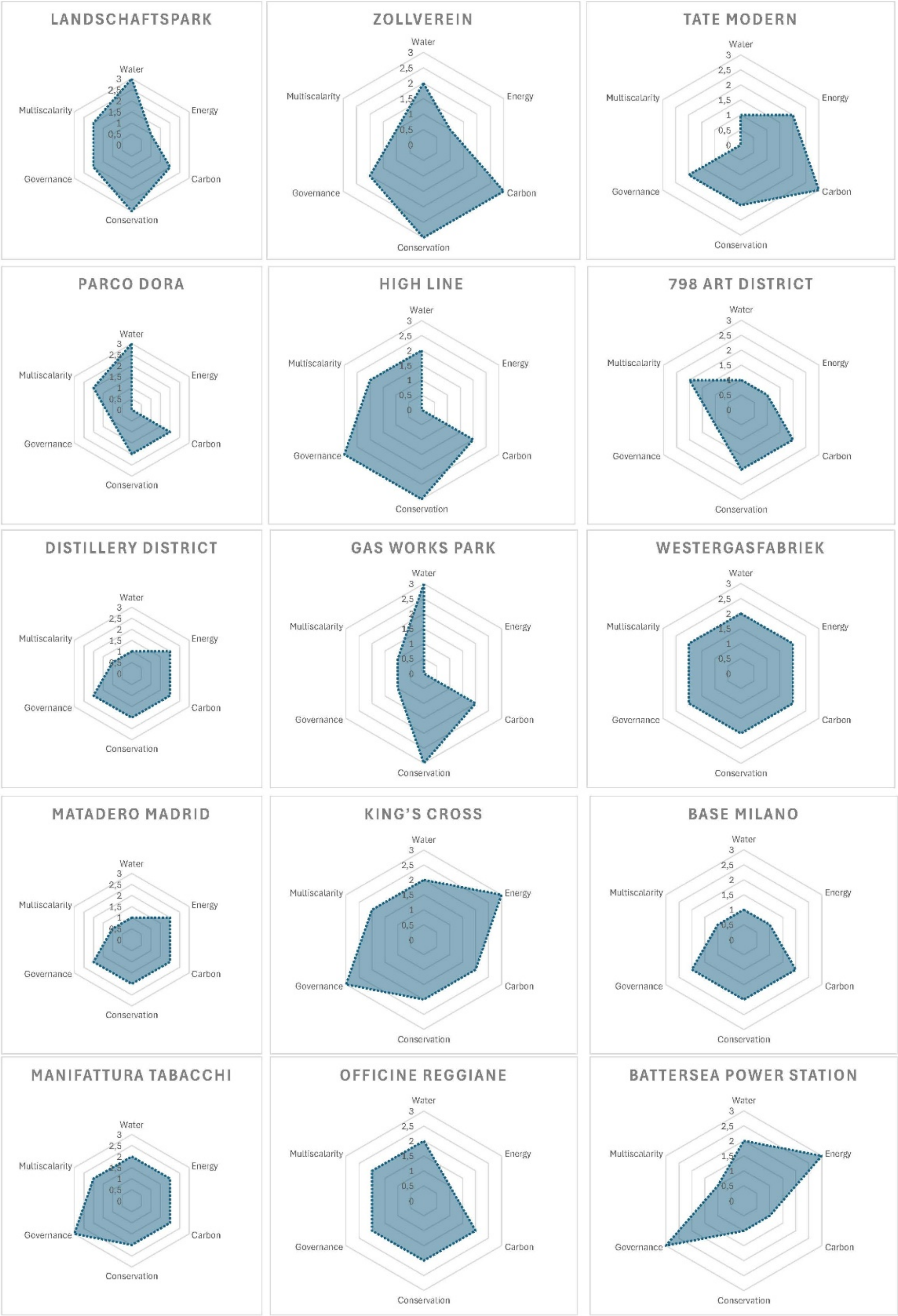
LANDSCHAFTSPARK
ZOLLVEREIN
TATE MODERN
PARCO DORA
HIGH LINE
798 ART DISTRICT
DISTILLERY DISTRICT
GAS WORKS PARK
WESTERGASFABRIEK
MATADERO MADRID
KING'S CROSS
BASE MILANO
MANIFATTURA TABACCHI
OFFICINE REGGIANE
BATTERSEA POWER STATION

Fig. 01 – Comparative analysis. Scoring assigned to the six dimensions defined for the evaluation of case studies

Tables

Category	Description
Indicators	Soil remediation; Sustainable Urban Drainage Systems (SUDS); green-blue infrastructure; water collection, treatment and reuse; hydraulic resilience
Metrics	% permeable surface area; m^3/year of reused water; % runoff reduction
Scale (0-3)	0 absent; 1 punctual; 2 integrated; 3 design driver

Tab. 01 – KPIs for the “Water” dimension assessment

Category	Description
Indicators	Envelope retrofit; energy demand reduction; renewable energy production; storage systems; local distribution networks
Metrics	kWh/m^2/year; % energy demand reduction; installed kWp; % self-consumption
Scale (0-3)	0 absent; 1 basic; 2 renewable production; 3 district integration

Tab. 02 – KPIs for the “Energy” dimension assessment

Category	Description
Indicators	% existing volume preserved; carbon stock; carbon emission reduction
Metrics	% primary structure preserved; $kgCO_2e$ avoided; LCA present (yes/no)
Scale (0-3)	0 marginal; 1 unquantified conservation; 2 structural; 3 explicit strategy

Tab. 03 – KPIs for the “Carbon” dimension assessment

Category	Description
Indicators	% primary structure retained; reversibility; volumetric transformation
Scale (0-3)	0 replacement; 1 partial; 2 structural; 3 integral

Tab. 04 – KPIs for the “Conservation approach” dimension assessment

Category	Description
Indicators	Management model; management plan; participation
Scale (0-3)	0 unstructured; 1 defined; 2 +plan; 3 +monitoring

Tab. 05 – KPIs for the “Governance” dimension assessment

Category	Description
Indicators	Territorial extent; shared networks; common infrastructure
Scale (0-3)	0 building; 1 site; 2 district

Tab. 06 – KPIs for the “Multiscalarity” dimension assessment

	Indicators					
Case Study	**Water (W) – Strategies**	**Energy (E) – Strategies**	**Carbon (C) – Strategies**	**Conservation Degree (Co)**	**Governance (Go)**	**Multiscalarity (MS)**
Landschaftspark Duisburg-Nord, Germany	Remediation, drainage, basins, green infrastructure	Energy demand reduction	Full preservation of steel structures	CI=3 – full conservation; TICCIH principles	Regional public management	District (MS=2)
Zollverein Coal Mine, Germany	Soil remediation	Limited efficiency improvements	Full preservation; UNESCO site	CI=3 – UNESCO protection, Nizhny Tagil Charter	Public-institutional foundation	Complex (MS=1)
Tate Modern, London, UK	Targeted water interventions	Efficiency + high-performance systems	Preservation of envelope and primary structure	CI=2 – structural conservation	Structured museum management	Building (MS=0)
Parco Dora, Turin, Italy	Urban remediation and drainage	Minimal energy demand	Selective structural preservation	CI=2 – partial structural conservation	Municipal management	District (MS=2)
High Line, New York, USA	Linear green + drainage	No renewable energy (RES)	Preservation of railway infrastructure	CI=3 – full structural conservation	PPP with foundation	Linear district (MS=2)
798 Art District, Beijing, China	Targeted interventions	Limited efficiency improvements	Widespread preservation of industrial sheds	CI=2 – structural conservation	Hybrid governance	District (MS=2)
Distillery District, Toronto, Canada	Reuse of courtyards and surfaces	Efficiency + selective renewables	Masonry preservation	CI=2 – structural conservation	Private management	Complex (MS=1)
Gas Works Park, Seattle, USA	Radical remediation, draining landscape	No renewables	Symbolic structural preservation	CI=3 – iconic full conservation	Public management	Site/Park (MS=1)
Westergasfabriek, Amsterdam, Netherlands	Remediation + integrated green	Efficiency + renewables	Selective preservation	CI=2 – structural conservation	Foundation	District (MS=2)
Matadero, Madrid, Spain	Limited interventions	System efficiency	Brick structure preservation	CI=2 – structural conservation	Public cultural management	Complex (MS=1)
King’s Cross, London, UK	Integrated blue infrastructure	Renewables + storage + local grid	Selective building preservation	CI=2 – structural conservation	Structured PPP	District (MS=2)
BASE (Ex-Ansaldo), Milan, Italy	Limited interventions	Basic efficiency	Primary structure preservation	CI=2 – structural conservation	Foundation	Complex (MS=1)

Manifattura Tabacchi, Florence, Italy	Urban green + drainage	Integrated renewables at district level	Selective preservation	CI=2 – structural conservation	Public-private partnership (PPP)	District (MS=2)
Officine Reggiane, Reggio Emilia, Italy	Remediation + reuse of open spaces	Efficiency improvements	Shed preservation	CI=2 – structural conservation	Public direction	District (MS=2)
Battersea Power Station, London, UK	Complex remediation	Structural renewables + advanced systems	Preservation of façades and main volumes	CI=1 – significant transformation	Capital-intensive PPP	Complex (MS=1)

Tab. 07 – Comparative analysis of selected heritage industrial adaptive reuse case studies

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