

Brief Report

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Brief Report

The Rise of AI-Enabled Startups in Creating a Low-Carbon Built Environment

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Abstract

The accelerating climate emergency demands urgent transformation of the built environment, a sector simultaneously responsible for substantial greenhouse gas emissions and highly vulnerable to climatic impacts. Rising global temperatures, extreme weather events, and increasing resource demands necessitate a holistic rethinking of building design, materials, and urban planning. This paper explores the potential of artificial intelligence (AI) as a catalyst for energy efficiency, circularity, and resilience in buildings. AI-driven tools—from generative design and predictive maintenance to digital twins and automated material flow analytics—enable optimization across the design, construction, operation, and end-of-life phases, reducing both operational and embodied carbon. Crucially, AI lowers entry barriers for startups, fostering an entrepreneurial ecosystem capable of delivering innovative, adaptive, and sustainable solutions in civil engineering. By integrating technological, regulatory, financial, and behavioral strategies, AI-enabled startups can accelerate the transition to a low-carbon, circular, and climate-resilient built environment. This paper argues that coordinated, multi-disciplinary action is essential: without it, the sector risks perpetuating vulnerable, carbon-intensive infrastructure; with it, civil engineering can evolve into a dynamic driver of sustainable innovation.

Keywords: climate emergency; built environment; generative AI; sustainability; circular economy; resilience

1. An unavoidable Climate Emergency

Global climate change is no longer a distant threat—it is an immediate and escalating emergency. In 2020, the United Nations Secretary-General called on all governments to declare a climate emergency until carbon neutrality is achieved. By 2024, the Earth’s annual mean surface temperature had risen approximately 1.64°C above preindustrial levels, one of the most extreme and persistent anomalies in modern climate history. This unprecedented warming signals that greenhouse gas accumulation and intensifying climate feedback loops are already reshaping the planet. The signs of this climate emergency are unmistakable. Extreme weather events—storms, heatwaves, floods, and droughts—have grown both in frequency and severity. Wildfires have nearly doubled over the past decade, burning almost 3 million hectares of forest each year. Rising sea levels, shifting precipitation patterns, and longer, hotter summers are no longer projections—they are realities already affecting millions of people worldwide. The built environment sits at the center of this crisis. Buildings are simultaneously major contributors to greenhouse gas emissions and highly vulnerable to climatic impacts. Yet the construction sector largely continues business as usual, showing limited capacity to adapt to rapidly changing conditions. Most structures were designed for historical climate patterns and are now ill-equipped to endure intensifying storms, extreme heat, or fluctuating humidity. Without a radical rethink of design principles, material selection, and urban planning strategies, our buildings risk becoming structurally and functionally obsolete. Immediate action is critical. Climate-resilient materials, adaptive design, and forward-looking planning must become standard practice. Retrofitting existing buildings, integrating passive cooling strategies, and planning cities to withstand extreme weather are essential measures. Transforming construction practices not only reduces

emissions but also strengthens human resilience against accelerating climatic threats. The climate emergency demands bold, comprehensive measures across all levels of the built environment. Only through decisive action can we ensure that our structures—and the communities that depend on them—remain safe, functional, and sustainable in the face of a rapidly changing world. Humanity's response in this decade will determine whether the built environment is a source of vulnerability or a foundation for resilience.

2. Reimagining Buildings in the Climate Emergency: AI, Energy Efficiency, and Circularity

The escalating climate emergency, driven in large part by rising energy demand and greenhouse gas emissions, underscores the urgent need to address energy consumption across all sectors. Nowhere is this more consequential than in the building sector, which represents one of the most energy-intensive components of the global economy and a pivotal determinant of resource use and emissions pathways. Projections indicate that worldwide demand for heating, cooling, ventilation, and other building services will rise substantially by mid-century, a trend that will intensify the sector's environmental burden unless transformative interventions are implemented. Recent comprehensive analyses — including the study showing that the cumulative carbon cost of constructing the global built environment over the past three decades puts the construction industry on track to double its carbon footprint by mid-century (Li et al., 2025) — highlight the scale and immediacy of the challenge and the need for systemic responses.

Achieving meaningful reductions in building-sector energy use and embodied carbon is inherently complex. Technical solutions—insulation, high-efficiency HVAC systems, heat pumps, passive design, and advanced glazing—are necessary but insufficient on their own. The problem spans political economy, regulatory frameworks, market incentives, financing mechanisms, professional practices, supply-chain structures, and household behaviours. Therefore, a holistic, interdisciplinary approach is essential. Policymakers must coordinate standards and incentives; industry and designers must adopt systems thinking and lifecycle perspectives; financiers must create mechanisms that reward low-carbon outcomes; and social scientists and communicators must facilitate behavioural shifts among occupants and building owners.

Behavioral change is a critical, often underappreciated, component of any comprehensive strategy. Energy consumption in buildings is mediated by countless daily human decisions—thermostat setpoints, shading behaviour, ventilation choices, equipment usage, maintenance practices—that are influenced by cognitive biases, social norms, and bounded rationality. Interventions grounded in behavioural science can increase the uptake of efficient choices: tailored guidance that accounts for household circumstances, bundled renovations that reduce transaction costs and complexity, and clear communication that highlights immediate, tangible benefits (cost savings, comfort improvements) alongside long-term environmental gains. Recognizing symbolic and social values—such as status associated with certain heating or cooling behaviours—can unlock additional pathways for adoption. Crucially, policies must reduce practical barriers to retrofits: simplified permitting, standardized retrofit packages, and financing instruments that spread upfront costs over time (e.g., on-bill financing, green mortgages) will increase uptake.

Complementary to energy efficiency, circular economy principles offer a route to drastically reduce the material-related emissions and waste arising from construction and demolition. The prevailing linear model—extract, manufacture, use, discard—not only wastes embedded value but creates supply chain vulnerabilities and environmental harm. Construction and demolition waste (CDW) volumes are large and projected to grow with urbanization and building activity; yet many of these materials retain substantial residual value and embodied carbon that can be preserved through reuse, high-value recycling, and design for deconstruction. Pathways to circularity in the built environment include prevention (building less or more efficiently), adaptive reuse of whole structures, component salvage, design for disassembly, high-quality recycling of metals, concrete substitution and reclamation, and material passports that track provenance and composition.

Operationalizing circularity faces several hurdles. Data inconsistencies and fragmented reporting practices complicate accurate assessment of recovery rates and embodied emissions; the absence of standardized, EU-wide (or globally harmonized) methodologies undermines comparison and inhibits investment. Economic development trends often show an initial increase in CDW generation before a decline—meaning the window to lock in circular practices is now. Technological innovations in recycling and material processing exist, but adoption has been limited by regulatory barriers, insufficient incentives, and immature markets for secondary materials. Gaps remain in collaborative governance and stakeholder engagement: effective CDW strategies require coordinated action across municipalities, waste managers, contractors, designers, and product manufacturers. Moreover, social sustainability must be foregrounded—ensuring local job creation, safe working conditions for salvage and recycling operations, and equitable access to circular benefits.

Integrated techno-economic and environmental assessments illustrate where gains can be achieved: reuse and recycling of high-embodied-energy materials (notably metals) deliver large greenhouse gas reductions and lifecycle cost savings. Conversely, landfilling and incineration produce higher net emissions and lock materials out of future value chains. Advanced management approaches—combining prevention, reuse, high-quality recycling, and AI-enabled material flow analytics—are therefore critical for sustainable CDW management. Digital tools such as Building Information Modeling (BIM), material passports, and RFID tagging can enable traceability, improve dismantling planning, and match recovered materials to new demand, but their potential is unrealized without clear standards, incentives, and capacity building.

At the same time, traditional approaches to construction—reliant on manual labour, tacit knowledge, and experience—are proving increasingly inadequate in fast-evolving project environments characterized by schedule pressure, complex supply chains, and heightened performance expectations. Conventional practices often produce inefficiencies: material over-ordering, inconsistent workmanship, and reactive maintenance regimes that allow small defects to become major failures. The consequences are multiple: higher upfront carbon through wasteful practices, reduced asset longevity, elevated lifecycle costs, and diminished resilience in the face of climatic shocks and operational variability. Unexpected disruptions—extreme weather, transport interruptions, or material shortages—expose the fragility of linear, labor-intensive workflows, undermining both project outcomes and environmental objectives.

Artificial intelligence (AI) offers a promising set of tools to address these shortcomings by enabling data-driven decisions across design, construction, operation, and end-of-life phases. AI methodologies—including machine learning, deep learning, computer vision, natural language processing, and hybrid models—can optimize designs to minimize material use and embodied carbon, anticipate construction challenges, automate quality assurance, and enable predictive maintenance. Xu and Guo (2025) highlight AI's potential to simulate human intelligence, analyze complex multivariate datasets, and provide actionable insights that improve efficiency and extend asset lifetimes. In design, generative algorithms can explore vast design spaces to identify configurations that meet structural, thermal, and material-use objectives simultaneously. In construction, computer-vision systems coupled with drones or site cameras can detect defects and safety hazards in real time, reducing rework and improving site safety. During operation, AI can enable fault detection in HVAC systems, predict energy loads, and orchestrate control strategies that match occupant needs with minimal energy use (Li et al., 2025a).

Empirical studies provide concrete evidence of AI's impact. Cai et al. (2025) demonstrate real-time multi-criteria decision-making frameworks that combine anomaly detection with secure, trust-based data handling to support cost-effective energy policy mechanisms. De las Morenas et al. (2025) show that near real-time Digital Twin systems, built on low-cost platforms, can predict energy consumption, facilitate load shifting, and manage HVAC systems efficiently for small and medium enterprises. Such systems increase operational transparency and allow targeted interventions that are both cost-effective and scalable.

AI can also accelerate circularity. Machine learning algorithms have been shown to estimate CDW quantities with high accuracy, supporting better procurement, planning, and recovery processes (Lakhout & Shaban, 2025). Deep learning models, combined with advanced sensors, can classify material types automatically at sorting facilities to improve recycling yields and economic returns (Langley et al., 2025). These capabilities enhance material recovery value chains and reduce the carbon intensity of subsequent construction activities.

Despite the promise, significant challenges temper enthusiasm. AI's effectiveness depends on data quality, coverage, and governance. Rare events—extreme failures, unprecedented weather patterns, or supply shocks—are by definition under-represented in historical data, limiting predictive accuracy for tail risks. Integration with legacy systems and fragmented data architectures is nontrivial; many projects lack digitized records or consistent metadata. High computational costs, opaque model behavior, and regulatory uncertainties (e.g., liability, privacy, certification of AI systems) further complicate deployment. Human factors matter: resistance among professionals accustomed to traditional methods, skills gaps in AI literacy, and organizational inertia can slow adoption. Hamilton (2025) finds that AI uptake is more likely when tools align with existing workflows, are user friendly, and clearly demonstrate measurable benefits; leadership and small-scale pilots are crucial to build trust and scale.

To translate AI's theoretical benefits into practice requires a coordinated agenda. First, invest in data infrastructure and standards: material passports, standardized metadata, and interoperable BIM conventions will enable consistent model training and reliable cross-project analytics. Second, adopt modular pilot projects that demonstrate ROI and reduce adoption risk; use outcomes to build best-practice playbooks. Third, create regulatory sandboxes that allow experimentation with AI for safety-critical tasks while ensuring accountability. Fourth, couple technological deployment with workforce development: training, re-skilling, and the creation of multidisciplinary teams that combine domain expertise with data science. Fifth, design finance mechanisms—performance-based contracts, shared-savings models, and green bonds—that reward energy savings, reduced embodied carbon, and circular material flows.

Ethical and governance considerations must be central. AI systems can amplify biases in data, create opaque decision pathways, and raise important questions about liability and transparency. Explainable AI techniques and participatory validation processes—where stakeholders review model outputs—can help ensure responsible adoption. Additionally, democratizing access to AI tools and avoiding concentration of capabilities in a few large firms will be important to ensure equitable benefits across regions and scales.

Research and policy agendas should also prioritize integrated assessment: combining lifecycle embodied carbon accounting with operational energy modelling, social impact appraisal, and economic feasibility. Cross-disciplinary research that brings together engineers, data scientists, behavioural scientists, economists, and urban planners is needed to design interventions that are technically sound, socially acceptable, and economically viable. Standardized metrics for circularity and resilience — alongside transparent reporting frameworks — will facilitate market differentiation and accelerate diffusion of best practices.

In conclusion, the intersection of rising energy demand, overwhelming flows of construction materials, and an accelerating climate emergency demands a dual focus: dramatically improving operational energy efficiency and reimagining the material lifecycle of the built environment through circular economy strategies. AI and digital technologies present transformative tools to support this transition but are not panaceas: they must be embedded within broader regulatory, financial, and social frameworks. By combining technical innovation with governance reform, behavioural insights, and market incentives, the building sector can reduce both operational and embodied carbon, manage CDW sustainably, and enhance resilience. The window for action is narrow; coordinated, evidence-based, and equitable interventions implemented now will determine whether the built environment becomes a vector of vulnerability or a foundation for a low-carbon, circular, and resilient future.

3. AI as a Catalyst for Innovation in Civil Engineering and the Built Environment

The integration of artificial intelligence into the built environment marks more than a technological increment; it signals a potential paradigm shift capable of redefining civil engineering's identity and positioning the discipline as a fertile ground for startup innovation. Civil engineering's historic mandate—managing rivers, spanning chasms, delivering shelter, and enabling mobility—rests on an ethos of reliability and risk-aversion. Because these projects are public-facing, physically consequential, and long-lived, the profession has long gravitated toward conservatism: established methods, incremental improvements, and a premium on demonstrable safety over speculative experimentation.

Low patenting activity and limited academically driven commercialization (Pacheco-Torgal et al., 2016, 2020) are symptomatic of an industry culture that traditionally privileges tried-and-true approaches, which in turn constrains the emergence, scaling, and investment appetite for deep-tech startups in the sector. Observed risks for construction-technology ventures—market uncertainty, marketing hurdles, misalignment with support organizations, low industry readiness, and onerous certification demands—underscore the persistent institutional frictions that blunt entrepreneurial momentum (Yucel & Azhar, 2023).

For decades, civil engineering innovation focused on incremental refinements rather than disruptive invention. Patents typically protect improvements in machinery, concrete formulations, or construction procedures that enhance efficiency or reduce cost; such advances improve project outcomes but rarely open entirely new technological frontiers. Interpreted through the lens of technological ecosystems, this pattern contrasts sharply with industries like biotechnology or information technology, where dense networks of startups, venture capital, universities, and agile regulatory pathways create rapid feedback loops for experimentation and scaling. Those ecosystems reward exploratory R&D, produce monetizable patent portfolios, and allow nimble firms to define nascent markets. The structural conservatism of civil engineering—regulatory complexity, unique project typologies, and high liability stakes—has historically discouraged similarly exploratory dynamics.

This contrast underscores civil engineering's structural conservatism: innovation remains largely utility-driven and application-specific rather than exploratory or science-driven. Several factors continue to reinforce this cautious approach. Construction is heavily regulated, with strict building codes, safety protocols, and environmental standards. Each project is often unique, making radical experimentation costly and complex (Wuni & Shen, 2020, Ali et al., 2023). Engineers and firms have traditionally favored solutions that are tested, auditable, and defensible, with regulatory compliance as a core design parameter. Even when new materials or techniques emerge, adoption remains slow, requiring review, pilot testing, and certification (Firoozi et al., 2024). Consequently, civil engineering innovation has emphasized refinement of existing practices over invention of entirely new methodologies.

Institutional misalignment exacerbates these challenges. Different stakeholders operate on divergent time horizons, speak distinct professional languages, and pursue contrasting incentives. Startups seek rapid iteration and market traction; owners and regulators emphasize long-term performance and risk reduction; investors prioritize scalability and exit prospects; and contracting firms focus on procurement cycles and subcontractor management. Unless these actors converge on shared metrics—performance, lifecycle cost, safety, and environmental impact—promising technologies risk being stranded between pilots and mainstream deployment. Walzer et al. (2024) illustrate this tension in construction robotics, showing how misaligned expectations and incentives prevent effective scaling even when the underlying technologies are mature.

Yet the pressures demanding change are unprecedented. Global population growth, urbanization, and climate-driven stresses require infrastructure that is energy-efficient, climate-resilient, and circular in material use. The scale of the challenge demands more than marginal improvements; it requires a reimagining of processes, business models, and professional identities.

In this context, AI emerges not merely as an add-on but as an enabling core technology that can alter how civil engineering conceives, designs, builds, and manages infrastructure.

AI’s capabilities are manifold and directly address many of the sector’s enduring pain points. It can ingest and synthesize massive, heterogeneous data streams—sensor outputs, climatic records, geotechnical logs, supply-chain telemetry, and historical maintenance reports—to reveal patterns that elude traditional analysis. Generative design algorithms can evaluate thousands of structural alternatives in silico, optimizing for weight, cost, embodied carbon, and constructability simultaneously. Predictive maintenance models analyze subtle shifts in vibration signatures or thermal profiles to flag incipient failures long before they become visible, thereby reducing downtime and extending asset life. Computer vision systems inspect welds, concrete pours, and on-site assemblies with repeatability that surpasses human inspection, reducing rework and safety incidents. Digital twins create virtual replicas of infrastructure, enabling safe, low-cost experimentation with materials, operational strategies, or emergency scenarios.

Crucially, AI lowers entry barriers for startups. Historically, entering civil engineering markets required substantial capital to test physical prototypes, access to large projects, and the tolerance for long sales cycles. AI allows many innovations to be prototyped and validated in software: energy-management algorithms, structural optimization routines, and maintenance prediction models can be trained and stress-tested on synthetic or historical datasets before any physical deployment. This shift reduces required upfront investment, accelerates iteration, and expands the range of feasible business models—software-as-a-service, performance-based contracting, and platform marketplaces for secondary materials, among others. The result is an expanded entrepreneurial landscape where smaller teams can experiment and scale without the prohibitive costs of hardware-first approaches. Several AI-enabled startups and projects have already demonstrated practical, low-carbon solutions for buildings, as summarized in Table 1

AI also offers constructive pathways to engage regulatory frameworks rather than bypass them. Explainable AI methods, rigorous validation protocols, and scenario testing via digital twins can produce evidence-based dossiers that help regulators evaluate safety and performance. By translating probabilistic model outputs into actionable risk metrics and traceable decision logs, AI can increase transparency and build confidence among certifying bodies. If regulators adopt standardized validation criteria for AI-driven tools—benchmarks for model robustness, interpretability requirements, and audit trails—innovation can proceed with accountability, accelerating approvals while retaining public safety.

Table 1. - AI-Enabled Startups in Low-Carbon Buildings.

Startup / Project	Location	Relevance
Ecoworks	Germany	Demonstrates AI scaling sustainable retrofits
BrainBox AI	Global	Shows operational carbon reduction and predictive energy efficiency
Converge	UK	Minimizes material waste, reduces carbon in construction phase
DecarbAI	Sweden	Adaptive energy use, demand response, predictive optimization
LuminLab	Ireland	Generates tailored retrofit plans, simulates renovation pathways
Centinel	USA	Optimize energy efficiency in buildings
Poliark	USA	Converts sketches or text into 3D models, streamlining design for architects and engineers, and reduces carbon at the design phase
Buildots	UK	Measures site performance and reduces delays by up to 50%.
Builtrix	Portugal	Predict energy consumption and support energy efficiency decisions in buildings
Build.ing	Portugal	Optimize construction processes, improve design–engineering integration, and shorten construction cycles

Adopting AI will rewrite professional practice and organizational dynamics. Civil engineering may shift from a craft-based profession centered on individual expertise to a data-centric discipline where decisions are co-produced by engineers and algorithms. This requires new competencies: data

literacy among engineers, domain fluency among data scientists, and cross-disciplinary teams capable of bridging methodological divides. Educational institutions and professional bodies must therefore evolve curricula and certification pathways to encompass data science, sensor engineering, ethics, and systems thinking. Firms should invest in reskilling and in institutional mechanisms—centers of excellence, interdisciplinary project offices—that enable rapid translation of algorithmic insights into field decisions.

Despite the promise, adoption barriers remain. Data quality and interoperability are persistent constraints: legacy projects lack standardized metadata, sensor deployments are inconsistent, and data governance frameworks are nascent. Many AI models require substantial, labeled datasets and robust validation to generalize across sites and climates. Organizational resistance—concerns about job displacement, liability, or loss of professional authority—can stifle pilots. Funding models need to evolve; investors and clients must reconcile the slower return profiles of infrastructure with the rapid iteration cycles of software. Finally, ethical and governance questions—algorithmic bias, transparency, and equitable access—must be proactively addressed to prevent technology from reinforcing existing inequalities or privileging well-resourced actors.

To realize AI's transformative potential, a coordinated, multi-pronged strategy is required. First, invest in shared data infrastructure: standardized ontologies for infrastructure assets, protocols for sensor data, and secure platforms for anonymized data sharing that protect commercial sensitivities while enabling model training. Second, deploy regulatory sandboxes that permit controlled experimentation under oversight, allowing safety-critical AI applications to be tested without endangering the public. Third, catalyze market demand through procurement strategies that reward demonstrable performance gains—energy savings, reduced lifecycle costs, or enhanced resilience—rather than narrow upfront metrics. Fourth, create financing mechanisms that align incentives, such as shared-savings contracts or resilience bonds that monetize long-term benefits. Fifth, foster university-industry consortia and incubators that blend civil engineering expertise with data science and product management to accelerate commercialization.

If these conditions are met, civil engineering's identity could evolve from conservative steward to dynamic innovator. Startups would not merely deliver incremental improvements but develop infrastructure that is adaptive, regenerative, and aligned with sustainability imperatives. AI-enabled buildings and networks will continuously monitor performance, learn from usage patterns, and autonomously adjust to maximize efficiency and safety. The built environment, once a static set of structures, will become a living, data-driven ecosystem capable of responding to environmental change and human needs.

This transformation will not be painless: it will require cultural shifts, institutional redesign, and sustained investment. But the alternative—perpetuating an industry model that struggles to meet the scale and speed of twenty-first-century challenges—risks leaving societies with brittle, carbon-intensive, and maladapted infrastructure. By embracing AI thoughtfully and equitably, civil engineering can not only protect public safety and asset longevity but also unlock a new era of entrepreneurship, economic growth, and sustainable infrastructure that serves both present and future generations.

4. Conclusions

The global climate emergency, driven by rising energy demand and material-intensive construction, requires urgent, systemic action within the building sector. Achieving meaningful reductions in operational energy use and embodied carbon demands a holistic strategy combining technical innovation, behavioural change, regulatory reform, and market incentives. Circular economy approaches—material reuse, high-value recycling, and design for disassembly—can significantly reduce construction and demolition waste while enhancing resource efficiency and resilience. Artificial intelligence emerges as a transformative enabler, capable of optimizing design, construction, operation, and end-of-life processes. AI facilitates predictive maintenance, generative design, energy optimization, and material recovery, while lowering barriers for startups and accelerating innovation in civil engineering. Yet, its potential depends on robust data infrastructure,

interoperability, workforce training, ethical governance, and supportive regulatory and financial frameworks. Integrating AI with circular economy principles, evidence-based policy, and cross-disciplinary collaboration can shift the built environment from a source of vulnerability to a foundation for sustainability, resilience, and innovation. The window for action is narrow: only coordinated, timely, and equitable interventions will ensure that the built environment supports a low-carbon, circular, and adaptive future.

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