

Opinion

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

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Abstract

The accelerating climate emergency places the built environment under increasing pressure as both a major source of greenhouse gas emissions and a system highly vulnerable to climate impacts. Buildings contribute substantially to global operational energy use and embodied carbon, while much of the existing stock remains poorly adapted to changing climatic conditions. This paper examines the role of artificial intelligence (AI) in improving energy efficiency, enabling circular material flows, and enhancing resilience across the building lifecycle. Based on a structured synthesis of recent peer-reviewed literature, institutional reports, and documented case examples, the study maps AI applications in design, construction, operation, and end-of-life stages, including generative design, predictive maintenance, digital twins, and construction and demolition waste analytics. The analysis shows how AI can reduce operational energy demand, optimize material use, and support reuse and recycling strategies, while enabling new software-driven business models in the building sector. The paper argues that AI's effectiveness depends on data availability, interoperability, regulatory alignment, and workforce capabilities, and that its benefits are maximized when integrated with circular economy strategies and supportive policy and financial frameworks. This integrated perspective highlights pathways for reducing emissions and improving the resilience of the built environment under climate stress.

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

1. An Unavoidable Climate Emergency

Global climate change is no longer framed solely as a long-term risk; it is increasingly recognized as an immediate and escalating emergency. In 2020, the United Nations Secretary-General urged governments worldwide to declare a climate emergency and to pursue carbon neutrality as a guiding objective for policy and development. Observational records indicate that by 2024 the Earth's annual mean surface temperature temporarily exceeded 1.5 °C above pre-industrial levels, placing recent years among the warmest in the instrumental record and at the upper bound of historical variability [1]. While individual years above this threshold do not constitute permanent exceedance of the Paris Agreement limit, they underscore the rapid pace of warming and the narrowing margin for mitigation.

This warming trend is consistent with the continued accumulation of greenhouse gases in the atmosphere and the activation of reinforcing climate feedback mechanisms. According to assessments by the Intergovernmental Panel on Climate Change, the likelihood and intensity of extreme weather events—including heatwaves, heavy precipitation,



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droughts, and tropical cyclones—have increased across many regions, with confidence levels ranging from medium to high depending on event type and geography. Observational and satellite-based datasets further indicate a marked rise in wildfire activity over recent decades, with global burned area and fire intensity increasing in several climate-sensitive regions, although regional variability and data uncertainties remain.

Beyond discrete extreme events, slower-onset processes such as sea-level rise, shifting precipitation regimes, and prolonged periods of extreme heat are already affecting ecosystems, infrastructure, and human settlements. These impacts are no longer limited to future scenarios but are increasingly documented in present-day risk assessments and damage reports affecting millions of people worldwide.

The built environment occupies a central position within this crisis. Buildings account for a substantial share of global energy use and energy-related carbon emissions, while simultaneously being highly exposed to climatic hazards. Despite this dual role, evidence from international assessments suggests that the construction sector continues to adapt more slowly than required. Building codes, materials, and design practices are still largely based on historical climate conditions, leaving much of the existing building stock poorly equipped to withstand intensifying heat, heavier rainfall, stronger storms, and increasing moisture variability.

Without a fundamental reassessment of design principles, material selection, and urban planning strategies, many buildings risk progressive loss of performance, safety, and functionality over their intended lifespans. Recent studies highlight the mismatch between projected climate conditions and current construction practices, particularly given low renovation rates and the long service life of most buildings.

Addressing this gap requires immediate and coordinated action. Climate-resilient materials, adaptive design strategies, and forward-looking planning must become integral to standard construction practice. Retrofitting existing buildings, expanding the use of passive cooling and ventilation, and designing urban environments capable of absorbing climatic shocks are widely identified as priority measures. Transforming construction practices can simultaneously reduce emissions and enhance societal resilience to accelerating climate risks.

The climate emergency therefore demands decisive and evidence-based interventions across the built environment. Actions taken during this decade will play a critical role in determining whether buildings become amplifiers of vulnerability or foundations for resilience in a rapidly changing climate.

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 [2]—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 behaviors. 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 behavioral shifts among occupants and building owners.

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 [3]; 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 labor, 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 [4] 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 [5].

Empirical studies provide concrete evidence of AI's impact. Cai et al. [6] 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. [7] 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 [8]. Deep learning models, combined with advanced sensors, can classify material types automatically at sorting facilities to improve recycling yields and economic returns [9]. These capabilities enhance material recovery value chains and reduce the carbon intensity of subsequent construction activities.

Alimi et al. [10] provide a comprehensive overview of the application of AI in Construction and Demolition Waste Management (CDWM). While these technologies show considerable promise, their deployment in real-world CDWM contexts presents a range of challenges that must be carefully considered. These challenges include technical performance limitations, difficulties in adapting AI systems to diverse environmental conditions, uncertainties surrounding economic feasibility, and important ethical concerns.

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 [11] 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.

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 [12,13] 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 [14].

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 [15,16]. 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 [17]. 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. [18] illustrates 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 span multiple subdomains, each addressing a distinct set of persistent challenges in civil engineering. At the data analytics level, machine learning systems can ingest and synthesize large, heterogeneous datasets—including sensor measurements, climatic records, geotechnical logs, supply-chain information, and historical maintenance reports—to uncover patterns that are difficult to detect using conventional analytical methods. In the design phase, generative and optimization algorithms can evaluate thousands of structural alternatives *in silico*, simultaneously balancing performance criteria such as structural efficiency, cost, embodied carbon, and constructability. For asset operation and maintenance, predictive models analyze subtle changes in vibration signatures, strain data, or thermal profiles to identify incipient failures well before they are visible, reducing unplanned downtime and extending asset service life. On construction sites, computer vision systems enable automated inspection of welds, concrete placement, and assembly processes with consistent accuracy, helping to reduce rework, improve safety, and support quality assurance. Finally, through digital twin frameworks, AI enables the creation of dynamic virtual representations of infrastructure systems, allowing engineers to test materials, operational strategies, and emergency scenarios in a low-risk, cost-effective environment.

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.

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

Startup/Project	Location	Building Lifecycle Phase	AI Technology Applied	Main Application	Carbon Impact & Relevance
Ecoworks	Germany	Retrofit/Renovation	Machine learning, digital twins, automation	Industrialized deep retrofits using prefabricated façade systems optimized by AI	Enables large-scale energy retrofits, significantly reducing operational carbon and embodied emissions in existing building stock
BrainBox AI	Global (Canada HQ)	Operation	Reinforcement learning, predictive analytics	Autonomous HVAC control and energy optimization	Demonstrated reductions of up to in GHG emissions and in energy use, targeting operational carbon
Converge	United Kingdom	Construction	AI-driven sensor analytics, predictive modeling	Concrete curing optimization and material performance monitoring	Reduces material waste, optimizes concrete use, and lowers embodied carbon during construction
DecarbAI	Sweden	Operation/Energy Management	Machine learning, demand forecasting	Adaptive energy use, demand response, thermal storage optimization	Turns buildings into flexible energy assets, reducing peak demand emissions and supporting renewable integration
LuminLab	Ireland	Retrofit/Planning	AI simulation models, decision-support systems	Personalized retrofit pathways and renovation scenario simulation	Improves retrofit decision-making, accelerating low-carbon renovation strategies
Centinel	USA	Operation	Data analytics, AI-based energy monitoring	Energy efficiency optimization and performance tracking	Supports operational energy savings and emissions monitoring in commercial and residential buildings
Poliark	USA	Design	Generative AI, NLP, 3D modeling	Converts sketches or text into 3D architectural models	Reduces design iteration time and design-phase carbon by minimizing rework and inefficient early-stage decisions
Buildots	United Kingdom	Construction	Computer vision, AI progress tracking	Automated site monitoring and construction performance analytics	Cuts delays (up to ~50%), reducing resource waste, idle machinery emissions, and construction inefficiencies
Builtrix	Portugal	Operation/ESG Reporting	Predictive analytics, AI energy modeling	Energy consumption forecasting and efficiency decision support	Enables energy optimization and ESG-aligned carbon reporting for building portfolios
Build.ing	Portugal	Design & Construction	AI process optimization, data integration	Design–engineering coordination and construction workflow optimization	Shortens construction cycles, reduces errors and rework, and lowers material-related emissions

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.

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 climate emergency and the material intensity of the building sector demand a shift from incremental efficiency gains toward systemic transformation. Reducing operational energy use and embodied carbon requires the integration of energy-efficient design, circular material strategies, behavioral change, and enabling regulatory and financial frameworks.

Artificial intelligence has clear potential to accelerate this transition by improving design optimization, construction efficiency, building operation, and material recovery across the lifecycle. However, AI is not a panacea. Its effectiveness depends on data quality, interoperability, workforce capabilities, ethical governance, and regulatory environments that allow innovation while safeguarding public interests.

Important research gaps remain. Limited evidence exists on AI performance under extreme and compound climate events, on the social and equity impacts of AI-enabled building technologies, and on how regulatory sandboxes or performance-based codes can support safe experimentation at scale. Addressing these gaps through interdisciplinary research and real-world pilots is essential.

By aligning AI deployment with circular economy principles, evidence-based policy, and inclusive governance, the built environment can evolve from a source of vulnerability into a foundation for resilience and sustainability. Timely, coordinated action in this decade will be decisive in shaping a low-carbon, adaptive future for buildings and cities.

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