International Journal of Computer Information Systems and Industrial Management Applications
ISSN 2150-7988 Volume 18(19s) 2026 pp. 646-657
https://doi.org/10.70917/ijcisim-2026-5072
Article

# Building Global resilience through Sustainable Innovation: A Case study approach

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**Abstract:** The most prominent engineering issues of the twenty-first century are climate change, rapid urbanization, water shortages, and growing energy consumption. The paper argues that a sustainable future necessitates a deliberate integration of energy innovation, infrastructure development, and climate research into a single engineering framework rather than isolated technical solutions. Global data is collected from the Intergovernmental Panel on Climate Change (IPCC), the International Energy Agency (IEA) and the International Renewable Energy Agency (IRENA). The paper first quantifies the scale and urgency of the challenge before examining how climate change threatens existing infrastructure through sea-level rise, extreme heat, flooding, wildfire, storms, and water stress. It then reviews the state of the global energy transition and the emerging discipline of smart, sustainable urban engineering. The core of the paper is a case study analysis spanning five Indian projects alongside five international benchmarks. These cases illustrate recurring engineering principles: systems thinking that couples energy, water and the built environment; the commercial viability of renewable energy at scale; and the outsized leverage of urban and agricultural engineering interventions. The paper concludes with a synthesis of the engineering imperatives required through 2030, including a tripling of renewable capacity, the scaling of green hydrogen, zero-carbon building codes, transport electrification, and nature-based infrastructure.
**Keywords:** sustainable engineering, green hydrogen, energy innovation, sustainable housing, renewable energy, agricultural engineering

## 1. Introduction

Innovative and sustainable engineering solutions have become critical to addressing the most pressing global challenges like climate change, rapid urbanization, water scarcity, and rising energy demand. Engineers now leverage a widening toolkit of technologies, including Artificial Intelligence (AI), the Internet of Things (IoT), and renewable energy systems, to design infrastructure that is not only functional but resilient, low-carbon, and equitable. There is an urgent and well-documented need to develop resilient infrastructure and eco-friendly practices that align with the United Nations Sustainable Development Goals (SDGs). Engineering is at the center of humanity's response to the climate crisis, and that the choices made in the next decade will determine the trajectory of the built environment for a century or more.

## 2. The Scale and Urgency of the Global Challenge

The share of the global population living in urban areas is projected to rise from 55% today to 68% by 2050. The Intergovernmental Panel on Climate Change (IPCC) identifies 1.5°C of warming above pre-industrial levels as the threshold beyond which climate impacts become significantly less reversible. Meeting a below-1.5°C pathway is estimated by the International Energy Agency (IEA) to require approximately USD 4.5 trillion in annual clean-energy investment by 2030.

| **8.2 Bn** | **1.5°C** | **68% by 2050** | **US$4.5 Tn** |
|---|---|---|---|
| World population (2024), +~80M/year | IPCC critical warming threshold | Global population living in cities | Annual clean-energy investment needed by 2030 |

*Table 1 — Indicators of the scale of the global engineering challenge (Sources: UN, IPCC, IEA)*

### *2.1 Global $CO_2$ Emissions by Sector*

Global $CO_2$ emissions reached an estimated 38.1 billion tonnes in 2025, according to the IEA Global Energy Review. The energy, power and heat generation sector remains the single largest contributor, followed by industry and manufacturing, transportation, buildings, and agriculture. This sectoral distribution is significant for engineering practice because it identifies where technical intervention yields the greatest emissions leverage: decarbonizing electricity generation and industrial processes offers the largest absolute reductions, while transport and buildings electrification offer the fastest-growing opportunity as renewable electricity displaces fossil fuels.

### *2.2 Global Temperature Trends*

NASA GISS data show the anomaly rising from a negligible +0.01°C in 1950 to +1.02°C by 2020 and +1.17°C by 2023, a trajectory that places the world close to the Paris Agreement's 1.5°C threshold. Independent analyses indicate 2025 was the warmest year on record, with an anomaly of approximately +1.47°C, reinforcing the urgency.

| **Year** | **Temperature Anomaly (°C)** | **Year** | **Temperature Anomaly (°C)** |
|---|---|---|---|
| 1950 | 0.01 | 2000 | 0.42 |
| 1960 | 0.03 | 2010 | 0.72 |
| 1970 | 0.08 | 2015 | 0.90 |
| 1980 | 0.26 | 2020 | 1.02 |
| 1990 | 0.45 | 2023 | 1.17 |

*Table 2 — Global average temperature anomaly, (Source: NASA GISS)*

## 3. Climate Change and Infrastructure Resilience

Climate change poses direct, quantifiable risks to existing and planned infrastructure across every major hazard category. Engineering resilient systems in a warming world requires that these risks be designed for explicitly, than treated as externalities.

| **Hazard** | **Engineering Risk / Impact** |
|---|---|

| | |
|---|---|
| Sea Level Rise | US$1 trillion of coastal infrastructure at risk by 2050; over 800 million people live in low-elevation coastal zones. |
| Extreme Heat | Roads, rail and bridges face buckling; construction labour productivity drops 10–15% above 35°C. |
| Flooding | Urban flooding costs US$82 billion annually; storm water systems in 70% of cities are under designed for current rainfall intensities. |
| Wildfires | Power-grid vulnerabilities cost the United States alone US$27 billion in wildfire-related outages since 2017. |
| Storms | Category 5 hurricanes are now 25% more frequent; building codes lag 20–30 years behind current climate models. |
| Water Stress | 40% of the global population faces water scarcity; the water infrastructure investment gap is estimated at US$6.7 trillion by 2030. |

*Table 3 — Climate hazards and their engineering implications for global infrastructure (Sources: World Bank, IPCC, IEA, NOAA)*

## 4. The Renewable Energy Transition

According to the International Renewable Energy Agency (IRENA), global renewable energy capacity has continued its sustained expansion into 2026, driven principally by solar photovoltaics and wind, both of which are now the cheapest source of new electricity generation across roughly 90% of the world. This cost trajectory is now the primary driver of renewable deployment, and it reframes the central engineering task as one of scaling supply chains, grid integration, and storage rather than proving technical feasibility. Significant engineering bottlenecks like permitting timelines, transmission capacity, critical-mineral supply chains, and grid flexibility all constrain the rate at which renewable capacity can be added.

## 5. Sustainable Cities: Urban Engineering for 2050

Cities consume approximately 75% of global energy and produce roughly 70% of global $CO_2$ emissions, despite occupying a small fraction of the Earth's land area. With urban populations projected to approach 10 billion people by 2050, urban engineering represents one of the highest-leverage domains for climate action.

### *5.1 The Engineering Smart City*

Technology-enabled urban systems are reducing resource consumption and emissions across six interconnected domains.

| **Domain** | **Engineering Intervention and Impact** |
|---|---|
| Smart Grids | Real-time demand management cuts peak loads by up to 30%; AI-driven load balancing integrates variable renewables. |
| Mobility Systems | Electric mass transit reduces urban transport emissions by 60%; integrated mobility apps cut car dependency by 25%. |
| Green Buildings | Net-zero commercial buildings are now viable at near-conventional cost; smart HVAC cuts building energy use by 40%. |

| | |
|---|---|
| Water Recycling | Advanced wastewater treatment enables 90%+ water reuse; Singapore recycles 40% of its water needs through NEWater. |
| Circular Waste | Zero-waste cities reduce landfill volumes by 85%+; industrial symbiosis parks share waste streams as inputs between firms. |
| Urban Greening | Nature-based infrastructure cools cities by 2–4°C; green roofs reduce storm water runoff by up to 75%. |

*Table 4 — Core engineering domains of the smart, sustainable city*

## *5.2 Review of literature*

Buliga, Scheiner, & Voigt (2016) address a question that earlier resilience research had largely left unstated: what specifically links a firm's innovation activity to its capacity to withstand shocks? They propose that business model innovation is the visible expression of adaptability, which they treat alongside robustness as one of two core components of organizational resilience. Radic, Herrmann, Haberland, & Riese (2022) push the more conceptual resilience literature toward something managers and researchers can put into practice. Their framework points to specific, observable practices diversifying revenue streams or supply sources, building redundancy into operational systems, and developing organisational capacity.

Geissdoerfer, Vladimirova, & Evans (2018) headline conclusion is that environmental and social value creation does not have to come at the cost of financial performance, and can even support it but only where firms manage to translate sustainability principles into genuinely operational practice. Geyer, Jambeck, & Law (2017) their finding that only a small share of all plastic ever manufactured has actually been recycled, with the great majority landfilled, incinerated, or released into the environment is routinely cited.

Chertow (2000) early review effectively established industrial symbiosis as its own area of academic inquiry, working through the existing literature to propose a working taxonomy: traditionally separate industries collaborating through the physical exchange of materials, energy, water, or by-products, with geographic proximity acting as the practical enabling condition. Jacobsen (2006) took the Kalundborg industrial park in Denmark already well known as an early, symbolic example of industrial symbiosis and it tracks specific material and energy exchanges among the site's power plant, oil refinery, and pharmaceutical producers over more than a decade, arriving at measured figures for water and resource savings.

Shah (2020) report for the Institute for Energy Economics and Financial Analysis examines the execution model behind India's gigawatt-scale "ultra-mega" solar parks, including the auction structures used to allocate capacity, the mix of public developers and private independent power producers involved, and the record-low tariffs these auctions have produced across successive bidding rounds. Nsoh et al. (2024) carried out a systematic review of the growing evidence base on Internet-of-Things and machine-learning-enabled irrigation systems, synthesizing findings across many individual studies rather than reporting a single deployment. Marquis, Toffel, & Zhou (2016) conducted a large cross-national study of corporate environmental disclosure and their key finding is that greater scrutiny tends to increase the overall volume of disclosure without proportionally increasing disclosure of unfavorable information in other words, scrutiny pushes firms to say more, but selectively, rather than to say more that is balanced. Kim & Lyon (2015) studied corporate environmental disclosure patterns and introduced a distinction that has since become influential in the accounting and strategy literature: greenwashing, in which firms exaggerate their environmental performance and understate genuinely good performance, often out of caution about future regulatory scrutiny or legal exposure.

Parguel, Benoît-Moreau, & Larceneux (2011) their argument is that self-reported disclosure, left unchecked, has weak internal incentives toward accuracy, whereas third-party ratings. bin Jumah (2024) conducted a comprehensive review of green hydrogen production, storage, and application pathways, working through the technological and economic literature to assess how close the technology actually is to the ambitious cost and deployment targets often cited in policy and industry materials. Irvine, Chua, & Eikass (2014) documented Singapore's water resource management strategy, known locally as the Four National Taps, which diversifies supply across local catchment areas, imported water, recycled NEWater, and desalination. Vallejo & Mullan (2017) writing for the OECD, examined the policy conditions needed for climate-resilient infrastructure to actually get built, financed, and maintained rather than remaining a stated ambition. Santamouris (2014) conducted a review of reflective and green-roof technologies used to mitigate the urban heat island effect and improve outdoor and indoor thermal comfort.

### *5.3 Research gap*

Existing studies tend to treat sustainable innovation and resilience as parallel themes rather than examining how one actively shapes the other in practice. Much of the current research relies on theoretical or conceptual models, with few empirical case studies capturing real-world implementation challenges. There is insufficient exploration of how resilience gained through sustainable innovation is sustained over the long term rather than just during immediate crisis response. There are very few studies which comprehend how sustainable future necessitates a deliberate integration of energy innovation, infrastructure development, and climate research into a single engineering framework rather than isolated technical solutions.

### *5.4 Scope of the study*

This paper adopts a case study approach to examine how the three pillars of climate science, infrastructure development, and energy innovation are being integrated in practice. Rather than treating these as separate domains, the paper demonstrates through ten detailed case studies drawn from India and abroad, that the most successful sustainable engineering interventions simultaneously address energy generation, water management, the built environment, and community livelihoods towards transforming the future.

### *5.5 Research Design*

Data for the research is collected from Secondary sources. Global data is collected from the Intergovernmental Panel on Climate Change (IPCC), the International Energy Agency (IEA) and the International Renewable Energy Agency (IRENA). To evaluate how climate science, infrastructure development, and energy innovation are integrated in practice, this paper analyses ten case studies selected to represent diverse geographies, scales, and engineering disciplines. Five are drawn from India, spanning community urbanism, utility-scale solar generation, precision agriculture, corporate campus sustainability, rural housing, and urban water-body restoration and five are drawn from leading international benchmarks in carbon-neutral urban planning, concentrated solar power, water security engineering, and hydraulic flood defence. Each case study is examined for its engineering approach, quantitative outcomes, and broader systemic impact, including common design principles. This paper uses thematic analysis as a qualitative research method to identify, analyze, and interpret patterns or themes within climate change, rapid urbanization, water shortages, and growing energy consumption, derived from case studies.

### *5.6 Objectives*

1. To examine the role of sustainable innovation practices in enhancing global resilience through a case study approach.
2. To identify the key strategies, challenges, and best practices adopted in integrating sustainable innovation to achieve resilience and competitive advantage.

## 6. Data Analysis -Case Study Methodology

## Case Studies — India

### *(1) Auroville, Tamil Nadu — A Living Laboratory for Humanity*

Founded in 1968 near Puducherry, Auroville is a township of approximately 3,500 residents from over 60 nationalities, spread across 3,930 acres and endorsed by UNESCO and the Government of India. It functions as a global experiment in sustainable living and has evolved into a research hub for solar energy, biochar, natural building, organic agriculture, and watershed management.

| **900 kW** | **70%** | **12M L** | **300+ acres** |
|---|---|---|---|
| Installed solar capacity (2024) | Renewable share of electricity | Rainwater harvested annually | Wasteland reforested since 1970s |

*Table 5 — Auroville engineering and ecological outcomes*

Auroville's key engineering solutions include solar and wind energy systems, rainwater harvesting and wastewater recycling, and green buildings constructed from compressed stabilized earth blocks, a technique promoted globally through the Auroville Earth Institute, which has trained architects in over 40 countries. Buildings using this method achieve interior temperatures 5–10°C cooler than conventional construction, without mechanical cooling. Solar capacity has grown from 30 kWp in 2000 to 900 kWp in 2024, and the settlement has reforested over 300 acres of degraded land, planting more than 50 native tree species in its green belt. Auroville demonstrates a systems-engineering approach in which energy, water, and housing are designed as a single integrated system rather than as independent infrastructure projects  reducing dependence on fossil fuels while achieving largely self-sustaining water systems. Its stated target is a fully renewable-energy township by 2050.

## *(2) Bhadla Solar Park, Rajasthan — The World's Largest Solar Power Plant*

Located in the Thar Desert of Jodhpur district, Bhadla Solar Park is the world's largest solar power plant, with an installed capacity of 2,245 MW spread across 14,000 acres of previously unproductive desert land. Commissioned in phases between 2018 and 2020, the park was developed jointly by NTPC, the Rajasthan Renewable Energy Corporation Limited (RRECL), the Rajasthan Solar Park Development Company, and private independent power producers, as a landmark project of India's National Solar Mission.

| **Phase** | Phase I (2018) | Phase II (2018) | Phase III (2019) | Phase IV (2020) |
|---|---|---|---|---|
| **Capacity Added (MW)** | 250 | 500 | 680 | 815 |

*Table 6 — Phase-wise installed capacity build-up at Bhadla Solar Park*

With annual solar radiation of approximately 5.8 kWh/m²/day, it’s among the highest in Asia the site is estimated to generate 15 billion kWh annually, powering over 7.2 million homes across Rajasthan and beyond. The project mobilized over ₹99 billion in capital investment, created more than 10,000 jobs during peak construction, and avoids an estimated 11 million tonnes of $CO_2$ annually relative to a coal baseline. Bhadla is cited as a catalyst toward India's target of 500 GW of installed renewable energy capacity by 2030.

## *(3) IoT-Enabled Smart Agriculture in Punjab*

Punjab, described as the granary of India, contributes approximately 19% of national wheat and 12% of national rice production from over 4 million hectares of cultivated land, but faces acute groundwater depletion, falling by an estimated 50 cm per year due to flood irrigation of paddy, along with soil and energy stress. The state has deployed IoT-based precision agriculture at scale across its 3.5 million farm holdings, using smart sensors, drone surveillance, soil-moisture probes, and AI-driven crop advisory systems under initiatives by the Punjab Smart Agriculture Project.

| **IoT Technology** | Drip + IoT Sensors | Weather-AI Irrigation | Variable Rate Technology | Soil Moisture Probes | Drone Monitoring |
|---|---|---|---|---|---|
| **Water Saved (%)** | 52 | 44 | 41 | 38 | 29 |

*Table 7 — Water savings achieved by IoT irrigation technologies in Punjab*

Measured outcomes from pilot deployments, such as in Ludhiana, are substantial: water use per acre has fallen from approximately 1,200,000 litres to 650,000 litres (a 50% reduction), fertilizer use has dropped from 155 kg/acre to 110 kg/acre, and average wheat yield has risen from 18 to 24 quintals per acre — a 29% increase. Farmers report additional net income of over ₹12,000 annually, alongside a 40% reduction in pest incidents through drone-based early detection and 60 lakh metric tonnes of food loss prevented annually through cold-chain IoT monitoring. The state's roadmap targets 1 million IoT-connected farms by 2027 and a fully digitized agricultural ecosystem by 2030, with an estimated ₹5,200 crore in annual savings potential.

### *(4) Infosys Mysuru Campus — Corporate Engineering at Scale*

Established in 2002, the Infosys Mysuru campus in Karnataka is the world's largest corporate training campus, spanning 350 acres with a training capacity of up to 25,000 employees at any one time. Campus integrates sustainability into its core infrastructure through LEED Platinum-certified buildings, on-site solar generation, rainwater harvesting, and a zero-liquid-discharge water system.

| **53%** | **100 MW+** | **95%** | **60%** |
|---|---|---|---|
| Renewable electricity share (FY24) | Solar capacity | Solid waste diverted from landfill (FY24) | Reduction in freshwater intensity since FY08 |

*Table 8 — Infosys Mysuru sustainability performance indicators*

Infosys' renewable electricity share rose steadily from 18% in FY18 to 53% in FY24, supporting the company's global carbon-neutral target, achieved in 2020, and a 42% reduction in per-capita energy use since FY08. On campus, 100% of wastewater is treated and recycled, and 34 rainwater collection points operate across the site. The campus illustrates how corporate engineering and sustainability can scale together, supporting over 25,000 employees while training approximately 350,000 engineering graduates annually and reducing the organization's carbon footprint.

### *(5) Sustainable Rural Housing in Assam and West Bengal*

The case is related to use of local, low-carbon materials mud, bamboo, and other regionally sourced inputs for climate-responsive rural housing in Assam and West Bengal. Passive cooling design eliminates the need for air conditioning while maintaining thermal comfort, and construction relies on traditional engineering knowledge adapted with modern technique. The approach supports local livelihoods and demonstrates that low-cost, scalable rural sustainability is achievable without high embodied-carbon materials such as cement and fired brick, offering a template for climate-responsive housing across similar agro-climatic regions of South Asia.

| **Dimension** | **Assam** | **West Bengal** |
|---|---|---|
| Primary hazard | Flood + seismic (Zone V) + cyclone | Flood + cyclone (coastal delta areas) |
| Government scheme | Pradhan Mantri Awaas Yojana – Gramin PMAY-G (22.60 lakh houses ) | Bangla Awas Yojana (34.11 lakh) |
| Innovation model | SEEDS-NEADS bamboo stilt housing (80 units, ₹75,000/unit) | MIT D-Lab bamboo roofing pilots |
| Material approach | Local bamboo + rubberized coating + concrete footings | Treated bamboo shingles/roofing sheets with locally sourced bamboo |
| Central assistance per house | ₹1,20,000 for plain areas, ₹1,30,000 for hill areas | ₹1,20,000 |

Table 9 — Sustainable Rural Housing in Assam and West Bengal

## 7. Case Studies — International

## *(1) Copenhagen, Denmark — Carbon Neutral City by 2026*

Copenhagen set out to cut citywide emissions by 67% relative to 2005 levels across a dense European capital of approximately 794,000 residents. The engineering solution rested on district heating — now 98% renewable — offshore wind generation, cycling infrastructure spanning 390 km of protected lanes, and mandated green roofs on new construction.

| | | |
|---|---|---|
| **67%**<br>Emissions cut (2005–2023) | **62%**<br>Daily commutes by bicycle | **1.2M t**<br>$CO_2$ saved per year via district heating |

*Table 10 — Copenhagen carbon-neutral city engineering outcomes*

Emissions fell from approximately 2.5 million tonnes of $CO_2$ in 2005 to 1.1 million tonnes in 2023, and cycling now accounts for 62% of daily commutes citywide.

## *(2) Morocco — The Noor Concentrated Solar Power Complex*

Facing dependence on imported energy for approximately 97% of national supply, Morocco set a target of 52% renewable electricity by 2030 and constructed a 580 MW concentrated solar power (CSP) plant featuring three hours of molten-salt thermal energy storage. The facility spans roughly 3,000 hectares of Saharan desert and uses approximately 3 million square metres of sun-tracking mirrors. The complex powers an estimated 1.1 million homes, reduces $CO_2$ emissions by approximately 760,000 tonnes annually, and employs more than 1,800 local workers, demonstrating that CSP with thermal storage can deliver dispatchable renewable power even after sunset, addressing one of the central engineering limitations of variable solar generation.

| **Category** | **Metric** | **Figure** |
|---|---|---|
| Scale | Total capacity | 582 MW (510 MW CSP + 72 MW PV) |
| Output | Annual generation | ~1,470 GWh |
| | Households served | 1.1+ million |
| | Share of national electricity | ~6% |
| Environmental Impact | $CO_2$ offset | ~690,000–762,000 tonnes/year |
| Policy Context | National target | 52% renewable energy mix by 2030 |

*Table 11 — Morocco — The Noor Concentrated Solar Power*

## *(3) Singapore — Engineering Water Security on a City-State*

Singapore's Four National Taps strategy is widely regarded as a global model for water engineering resilience on a land- and resource-constrained city-state. The strategy diversifies supply across four independent engineered pathways: A Local catchment where rainwater capture across two-thirds of the island's land area, supported by an extensive reservoir network. NEWater (recycled water) is advanced membrane and UV treatment of wastewater, meeting approximately 40% of national water demand. Desalination in five plants supplying approximately 30% of national water demand. Imported water is a long-standing supply agreement with Malaysia, alongside demand-side efficiency that has cut per-capita consumption from 165 to 130 litres per person per day.

| **Metric** | **Figure** | **Explanation** |
|---|---|---|
| Current water demand | ~440 million gallons/day | Current demand stands at 440 million gallons per day |

| | | |
|---|---|---|
| Total production capacity (all 4 taps) | ~782 million gallons/day | Total production capacity across all four taps stands at 782 million gallons per day |
| NEWater capacity | ~760,000 m³/day | The NEWater factories in Singapore have a supply capacity of 760,000 m3/day |
| Desalination target by 2060 | up to 30–50% | Sources vary — up to 30 per cent of Singapore's future water needs by 2060 vs. up to 50% by 2060 |

*Table 12 — Singapore — Engineering Water Security*

### *(4) The Netherlands — Delta Works Flood Defence*

Subsequent to the catastrophic North Sea flood of 1953, which killed 1,836 people, the Netherlands undertook the largest hydraulic engineering project in history: the Delta Works. The system now protects 26% of the country that lies below sea level, comprising storm surge barriers with 210-metre movable wings, an 8 km moveable barrier that preserves tidal ecosystems, and a network of 13 dams, locks and barriers spanning 700 km of coastline.

| | | |
|---|---|---|
| **700 km**<br>Protected coastline | **€8 Bn**<br>Total investment (2024 terms) | **1-in-10,000**<br>Year storm event resistance |

*Table 13 — Netherlands Delta Works engineering scale*

Engineered to withstand a 1-in-10,000-year storm event, the Delta Works now protects 17 million people and has become a template the Netherlands exports internationally, advising flood-defence programmes in Bangladesh, Vietnam, and New Orleans.

### *(5) Costa Rica — Renewable Energy Resilience*

Costa Rica's electricity grid is one of the cleanest in the world, though 2024 exposed how weather-dependent that resilience really is. Fossil fuel import dependency and vulnerability to hydrological volatility (droughts affecting hydropower). Diversified renewable portfolio to buffer against climate-driven drought risk paired with reforestation as a resilience/carbon-sink strategies.

| Metric | Value |
|---|---|
| Renewable share of electricity generation | 98.6% |
| Low-carbon share of generation | >98% |
| Planned new generation capacity | 600 MW |
| Per-capita low-carbon generation | 2,519 → 2,494 kWh |

*Table 14— Costa Rica  Renewable Energy*

## 8. Innovation Frontiers: Green Hydrogen and the Circular Economy

### *8.1 Green Hydrogen*

Renewable-powered electrolysis is increasingly viewed as the missing piece required to decarbonise steel, shipping, aviation, and other heavy industrial processes that cannot be electrified directly. The cost of green hydrogen has fallen sharply, from approximately US$5.50/kg in 2020 to US$3.20/kg in 2024, with projections of US$1.50/kg by 2030 and approaching US$0.90/kg by 2035, approaching cited US$1/kg target for cost competitiveness with fossil-derived hydrogen.

| Year | 2020 | 2022 | 2024 | 2026E | 2030E | 2035E |
|---|---|---|---|---|---|---|
| **Green Hydrogen Cost (US$/kg)** | 5.5 | 4.8 | 3.2 | 2.5 | 1.5 | 0.9 |

*Table 12 — Projected cost trajectory of green hydrogen production*

The IEA targets 500 GW of global electrolyser capacity by 2030, and hydrogen is projected to meet approximately 14% of global energy demand by 2050. Announced investment into hydrogen infrastructure globally has reached an estimated US$300 billion, reflecting growing confidence hydrogen will play a structural role in decarbonizing.

### *8.2 The Circular Economy*

Globally, only 9% of plastic material is recycled; 54% is landfilled, 14% is incinerated, 12% is composted or biologically processed, and 11% is littered or otherwise unaccounted for. Addressing this gap requires engineering design changes at the product level as much as improved waste management. Design-for-disassembly principles, under which products are engineered so that all constituent materials can be recovered, are gaining traction.

## 9. Findings

Several conclusions follow from the evidence and case studies presented above. The scale of the required transition is unprecedented, but the underlying engineering tools already exist; what is now required is speed, scale, and political drive rather than further proof of technical feasibility. Renewables have become cost-competitive, with solar and wind now the cheapest form of new power generation across roughly 90% of the world, fundamentally shifting the economics of the transition in engineering's favour.

Cities remain the primary leverage point, since approximately 70% of global emissions originate from urban areas, meaning that urban engineering interventions of the kind demonstrated in Copenhagen and across the Indian smart-city and case studies, have an outsized effect on global outcomes relative to their local scale. Innovation across green hydrogen, artificial intelligence, and circular design is moving from experimental deployment to mainstream adoption faster than earlier projections anticipated. Finally, the case studies collectively demonstrate that engineers must lead rather than merely execute: the technical solutions required for a sustainable future demand engineering leadership within policy, investment, and design processes, not simply implementation once decisions have been made elsewhere.

## 10. Conclusion

The engineers of today are building the infrastructure their successors will inherit. The evidence assembled in this paper, from global climate and emissions data, through documented infrastructure risk, to ten detailed case studies spanning India and international benchmark projects, demonstrates that the technical knowledge required to build a sustainable future already exists. Auroville's integrated energy-water-housing systems, Bhadla's record-low-cost solar generation, Punjab's IoT-driven water savings, Copenhagen's carbon-neutral transformation, and the Netherlands' century-spanning flood defences each show, in a different domain, that climate-resilient, low-carbon infrastructure is not merely theoretically possible but has already been engineered and operated at scale.

Six imperatives stand out as the minimum required to remain on a pathway consistent with the 1.5°C target. Triple renewable capacity by deploying approximately 1,100 GW per year, three times the 2023 rate, with supply chains, permitting, and grid capacity as the principal engineering bottlenecks. Phase out unabated coal so that no new coal plants, with approximately 500 GW retired globally by 2030, alongside engineered just-transition plans for coal-dependent communities across Asia, Africa, and Eastern Europe. Scale green hydrogen electrolysis capacity to 100 GW by 2030, with parallel development of storage, pipeline, and end-use infrastructure, targeting production costs below US$2/kg for mass adoption. Achieve zero-carbon buildings, net-zero building codes across all major economies, retrofitting approximately 1% of existing building stock annually, and deploying heat pumps at roughly ten times the current rate. Electrify transport, 50% of new car sales electric by 2030, supported by charging infrastructure engineered for approximately 300 million electric vehicles, and decarbonizing half of urban transit systems globally. Deploy nature-based infrastructure by protecting and restoring 30% of land and sea, integrating natural flood management, urban forestry, and wetland restoration into mainstream infrastructure design rather than treating them as supplementary measures.

The central question is therefore not whether the engineering knowledge exists to address climate change, but whether the profession, and the institutions that fund and regulate it, act with the speed, scale, and ambition the evidence demands. Integrating climate science, infrastructure development, and energy innovation into a single, systemic engineering discipline, as illustrated throughout this paper, offers the clearest path toward that outcome.

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