Chapter-23

Advancing Environmental Resilience through Science, Technology, and Engineering

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Abstract

This chapter explores the critical role of science, technology, and engineering in advancing environmental resilience amid accelerating climate change and socio-ecological challenges. It emphasizes resilience as the capacity of interconnected systems—natural, human, and engineered—to adapt, absorb, and recover from disruptions. The discussion highlights the importance of systems thinking, innovation, and nature-inspired solutions such as biomimicry in addressing complex environmental issues. It further underscores the role of data, open science, and interdisciplinary collaboration in improving decision-making under uncertainty. Engineers are presented as key agents of change, responsible for integrating sustainability, equity, and ethical considerations into technological design and implementation. The chapter also examines challenges in scaling innovations from laboratory to real-world applications and the importance of policy, partnerships, and community engagement in ensuring successful adoption. Ultimately, it calls for a holistic, inclusive, and responsible approach to building resilient systems that support environmental sustainability and societal well-being.

Keywords: *Environmental resilience; Climate change; Sustainability; Systems thinking; Innovation; Biomimicry; Data science; Engineering solutions; Socio-technical systems; Community engagement; Policy and governance; Ethical innovation; Adaptation; Interdisciplinary approaches; Sustainable development*

Prologue: The Whisper of a Changing Planet

Under the unyielding, specter of climate change, the fragility of civilization and potentially life itself is exposed; threats cascade through interconnected systems of land, air, water, and infrastructure; enduring survival hinges upon not myths of equilibrium but the design of human, engineered, and natural systems for resilience—resilience as secured with the participation of scientists, engineers, community advocates, and sociologists (H. Sherfy, 2019).

2. Chapter One: The Call of Resilience

Every day—indeed, every hour—a great number of natural and human sciences confront the calamitous signals of planetary change; from all points of the compass new facts arrive, the indelible marks of a world unwinding under the twin pressure of too-much and not-enough.

What is at stake if no course adjustment occurs is nothing less than a fundamental alteration in the character of the planetary climate, the environment that undergirds all terrestrial life, the oceans and the agriculture from which humanity has derived its greatest cosmic conveniences in terms of energy, protein, fats, sugars, fiber, water, and so on.

Resilience this much must mean—the capacity from the individual to the ecosystem to absorb and to recover from rapid unforeseen changes without loss of self-definition—if the uncertain burden of preliminary information broadcasts from late-night webcams at 25 meters above sea-level has any design to induce preparatory action.

For systems of any kind there can be no ruggedness to a single perturbation in behavior alone, nor even to the regular series of perturbations in behavior that characterize the quotidian. To be resilient against uncertain pressure requires another interpretation of systems themselves.

An adequate form of resilience must therefore find occasion for attention to the functional organization of the situation as a whole—the entire suite of mutually coupled, reciprocally constraining signal pathways—and to the identification of large-scale change in just some higher-regime principle of operation. To be properly forward-looking and precaution-oriented, attention must be directed to the very processes of interconnection that the situation is stubbornly seeking to hide from view.

Throughout the price-staggered approach to hydrocarbons of the past decadal cycle through shifting time-windows of regulation and availability, what has been manifest to the eye is neither the coming of a techno-multiverse nor the enabling of a bona fide innovation priority but rather the fitting-forward of progressively more functional combinations of existing technologies that the regime in change only seems to conceal (Bryant and Allan, 2013).

The partial observation stands forth then, as it could scarcely do otherwise after four centuries of experimental exploration by the discipline, that the same full-chain functional regime specified against that compound of hydrocarbons and made real in all aspects from hard-ware to thinking in present application too eminently satisfies and enables after change too by any number of alternative media in their own hallowed right without the need for recourse to altogether novel primitives or even to an increase in functionality per se (Muntasir, 2017).

On a brownfield site the proposal awaits timely implementation, and the process of deployment for the combined strategy of guidance seeking does still accordingly remain traceable in its totality.

Chapter One Continued: Systems Beneath the Surface

Contemporary systems theorists in a variety of disciplines have posited that when dealing with societal or environmental challenges such as those posed by unequal economic and social systems, climate degradation, widespread extinctions, estuarine health, and pandemic resilience, the “systems beneath the surface” are often the key to emancipation and resilience (A. Burke et al., 2017). Much attention can be paid to surface phenomena — the economy, infrastructure, land use, water governance, recreation, habitats, vegetation, and carbon deposits — and still misinterpret systems dynamics, overlook rich opportunities for positive change, and persist in poverty, detrimental land use, pollution, and vulnerability to hazards. In these terms, an interconnected urban-rural-riparian-ecosystem paradigm applied to central New Mexico illustrates the richness of "the systems beneath the surface." Such spatial perspectives also provide glimpses of useful leverage points. The underground hydrology, atmosphere, food networks, energy resources, and infrastructure configurations of the Albuquerque Metropolitan Area and the surrounding watershed extend outward from the city's center and together embody both environmental vulnerability and opportunities for resilient design. A series of counterfactual scenarios regarding the past history of Albuquerque further illustrates how a number of "hidden" interactions could positively or negatively affect contemporary environmental conditions. A conceptual framework that emphasizes co-arising underground hydrology, surface soil moisture, agricultural extraction, and atmospheric feedback represents another implementation of a "systems beneath the surface" perspective.

3. Chapter Two: The Loom of Innovation

In human culture as much as nature, weaving marries the art of tying different threads together, the loom of innovation similarly spans the space between challenges and solutions: in innovation, as in weaving, the necessary tools are only part of the answer—one must also know the right threads and the order in which to place them; yet, despite modern distinction between art and craft, weaving, dominated by female artisans, remained the domain of—often lay—scientists, while innovations born from scientists' or engineers' instinct for crafting rather than ideas and mathematics embraced the creative heart of art; contemporary development of sustainability and resilience embody processes of weaving within these dual meanings of the innovation loom: successful approaches start with defining clearly the problem to be solved, the question of which is increasingly important amidst diverse concerns over climate change, urban air quality, or urban flooding; complex, complex urban, rural, or ecological systems interlink elements, boundaries among them flow, yet functioning and interactions throughout the system generally follow distinct rules or species lead to major function changes even under slight parameter tuning; sustainability and resilience thus interdefine and feedback sustainability level influences the resilience performance of infrastructure, services, institutions, and environment; conflict between sustainable development and human welfare—and between long- and short-term economic or human welfare—impedes widespread adoption of resilience-centred value; whilst decades of service, mass expendable consumption decouples consumer efforts to maximize service from large-scale resource or space waste through careful design sip readily available urban and economic recycling to unlocking sustainability improvement and resilience advantage; together stem from resilience-oriented thinking; surfaces of urban rural ecological systems deteriorate a-layer urban areas; human depth underground; yet urban, rural, and ecological remain above-ground. (A. Ashford, 2009)

4. Subchapter: Nature-Inspired Solutions

Biomimicry—a method that draws inspiration from nature—offers a remarkable pathway to environmental resilience (W. Whelchel et al., 2018). The clandestine designs of nature sustain complex systems, echoing the laws of physics, chemistry, or biomechanics. Unlike conventional engineering, bio-inspired design attunes to lessons from living organisms that have endured 3.8 billion years of identical planetary constraints. For example, the density and distribution of sweltering red fire ant mounds help to regulate climate within the frequently temperature-extremes of the exteriors. Besides resilience, the heuristic of analogical reasoning generates potentially cost-effective, sustainable, and adaptive solutions that satisfy the multi-dimensional criteria of society, economy, environment, and politics.

Urbanization, climate, and socio-political changes propel the materialization of complex environmental problems like floods, droughts, landslides, etc. Records at the time of day, rainfall-rainfall, and weight collected by water-sensors can properly help nowadays comprehensive environmental problems like Urban Flood Modeling. Modern societies acquire multi-dimensional data through diverse sources that can be employed by deterministic or stochastic data-processing approaches to generate premises and projections of environmental situations that immensely facilitate the analysis of environmental problems. Sensors can concurrently acquire long- and short-term and data of different species and help to understand their interactions and transitions of environmental situations. In addition, modelling still carries uncertainties. To strengthen the planning and collaboration of scientific research which can save the time, resources, and expense that would belong to citizens, numerous data have remained hidden or jammed due to the production or publication right, hindering the co-construction and co-edition of uncertainty models by scientists at nationwide or even worldwide scales.

4.1. Subchapter: Data as a Compass

Data inform decisions when they are comprehensive, precise, and pertinent, directing policy when visibility into interconnected systems is inadequate. Common data types include global or regional standard data, local measurements from urban sensor networks, land-use and land-cover information, and phenomena-specific models; rich detail supports complex analysis, while joint models are necessary to illuminate interactions among interconnected systems. Wherever multiple models interact and disseminate information, uncertainties cascade, complicating comprehension of individual processes; policy cannot disregard such uncertainty. Open science enhances the reproducibility and transparency of analysis, algorithms, and models, enabling downstream assessments of uncertainty, while documented post-processed indicators modify behaviour across public domains, applications, platforms, and services (J. Hollaway et al., 2020).

4.2 Chapter Three: Engineers of Change

Engineers of Change

Science, technology, and engineering play a crucial role in supporting, enhancing, and shaping innovations that have the potential to influence resilience in interdependent systems at local, regional, and national scales. Engineers become agents of change when they apply their art, craft, skills, and knowledge to processes and products that address resilience, adaptation, and sustainability—concerns that are especially critical given the large-scale changes occurring in the environment and the serious implications they hold for society. A great span of societal challenges and global constraints, such as poverty and conflict, align the practice of engineering with the moral and ethical dimensions of total environmental change (I. Eseonu and Hammar, 2019). The core principles of action for engineers can be simplistically grouped into three areas. One centers on the idea that technological solutions can encompass sustainability and resilience, particularly when they are placed into decision-making and governance contexts. A second principle focuses on extending access, through affordable and appropriate forms of technology, to widespread segments of society unable to gain access or remain connected to critical systems in an ever-more-connected world. The third emphasizes the importance of artifact design that goes beyond traditional considerations such as safety and reliability, and proactively integrates principles of equity, access, and social justice guidance into decisions at all stages of a technological artifact's life-cycle.

Larger systems and society also play an important role shaping resilience pathways pursued on militarized, limited, and scaled operative engagement. Engagement toward consideration of resilience therefore meaningfully connects with local or context-based engineering but also includes considerations of limited capacity of local and context-based of those considerations as the first two principles defined above. Attention to needs for improved resilience can overcome constraints of technology over these and similar other challenges by proceeding at the same time on articulated socio-technical44 problems of resilience via a second broader interpretation of active consideration of "equitable" or "equity-driven."

5. Subchapter: Building with Careful Hands

Engineers as agents of change actively seek ways to improve social resilience and ecological health through their work. Like other STEM practitioners, engineers leverage science, technology, and engineering-based expertise to drive innovation in products and services. What sets engineers apart is their primary connection to the act of making—catalyzing the translation of ideas into tangible artifacts and their performance in the real world. Throughout that creation process, engineers—and institutions and organizations that employ their expertise—are often responsible for guiding a product's impact on society and the environment. A suitably comprehensive expression of such trends and tendencies is: Engineering, in its broadest sense, is the application of science and mathematics to solving problems through the creation of technical artifacts. The practice of engineering translates that conception into action in a deliberate and considerate manner.

Specific engineering projects implement that idea through technical pioneers, designers, and makers engaged in applying science and mathematics to a particular problem, developing appropriate technical artifacts, and addressing benefits and risks to society and the environment. Social engineering addresses human behavior, opinion, and perception; economic engineering centers on pricing and incentives; other disciplines guide policy, planning, and decisionmaking. Pointing those responsible for all of those aspects toward an agreed-upon goal pushes any of those activities toward producing positive outcomes. Positive outcomes occur when a product performs better than an equivalent on a previously established basis—cost, effectiveness, efficiency—or provides an additional important quality, such as being more robust or adaptable.

5.2. Subchapter: Communities at the Core

Effective engaged research requires trust-building and relationship development, which are essential for community involvement in engineering design and innovation; the approach emphasizes “going to Gemba” to include community voices in early design phases, rather than after initial concepts are developed, fostering better understanding of technology impacts and enabling engineers to incorporate community input as important design requirements; trust is crucial in university-community partnerships, especially given power disparities; thus, the approach promotes collaboration and bilateral learning through transformational relationships to achieve effective engagement and mutual understanding.

6. Chapter Four: From Lab to Landscape

Convincing the environmental community to adopt innovative techniques requires navigating technical, economic, and socio-political hurdles (J. Hollaway et al., 2020). While straightforward mechanisms exist to transition ideas from laboratories to real-world applications − such as matching experimental studies with infrastructures and environmental systems or devising policies for new technologies − other approaches are either indirect or require building entirely new conditions (Parodi, 2010). Changing the socio-political context for a technology like large-scale energy storage or a practice like hydrocarbon extraction remains much more difficult than establishing regulations for a simpler solution such as a stormwater-best-practice application or permitting a resurfaced pavement with higher permeability. Lessons drawn from these examples reveal valuable insights shaping the evolution of resilience.

Turbulent shifts weave complexity into contemporary life. People across nations, landscapes, and communities face interconnected threats to well-being ranging from extreme weather to global inflation. Within public life, the balance of political acceptance, market behaviour, and climate action coordinates these challenges, yet the interface among intra-system feedbacks and across-system interdependencies multiplies the dimensions of tension-building. No corner of life, no profile of person, and no shade of fabric remains untouched by today’s biodiverse and cross-generational realities. For Caribbean, Pacific, and coastal communities, the unfolding human-centred climate crisis compounds the economic disruption wrought by COVID-19, exacerbating multiple facets of well-being and seeking urgent supplementary channels from public budgets, private investment, and international philanthropy.

6.1. Subchapter: Scaling Technologies for the Real World

Many innovative technologies developed in controlled laboratory environments struggle to achieve broad adoption in larger-scale demonstration projects, further underscoring the challenge of transitioning to the real world. For a variety of reasons, technologies that function reliably at small scales may not scale effectively to larger dimensions or greater complexities. Up-scaled systems may not exhibit anticipated benefits realized during small-scale trials, leading notably to unexpected environmental and public health stresses. Urban green rooftops can stabilize indoor temperatures, yet when employed at scale, some designs have drawn exposure insecurities as a consequence of unintended air-flow reversals. Fuel cells approaching commercial readiness for stationary systems would also require distinctly different design considerations—and possibly even new hydrogen sources—for transportation applications. Deployment of a promising multilayer polymeric barrier for water and gas-tight containers has not materialized after decades of research, in part because commercial interests surrounding an entire spectrum of polymeric materials must be re-imagined before wide-scale adoption appears feasible.

In addition to operational considerations, diverse contextual, regulatory, institutional, and economic factors bear critically upon technology advancement and deployment. Environmental technologies promising substantial benefits at large scales frequently find themselves impeded by uncertain or segregated decision authorities and funding opportunities spanning component manufacture, integration into distribution and use infrastructures, and end-of-use disposals. Coordinated examinations thus become essential to determine whether, how, and under what combinations and configurations selected candidates may demonstrably contribute in economically viable terms at localized safety levels to socioeconomic, technological, and ecological sustainability, climate normalization, eco-refreshing, urban partitioning, and deep carbon-fuel elimination through replacement. Specific roadmaps can then guide expansion trajectories, working closely with regulators, community agencies, funds-sourcing, educational institutions, venture-capital firms, and similar pivotal stakeholder enterprises. Moving toward organic and biodegradable plastic sheeting offers an instructive instance; screening focused upon environmental footprint, human health impacts, integration impedance, cost-benefit ratios, and other important considerations accelerated the resultant assessment process dramatically.

6.2. Subchapter: Policy, Practice, and Partnerships

Policy-making processes, public sector regulation, and private sector practices greatly affect the social-economic-environmental realities that inform and condition resilience—through present-day decisions and long-term investments. So resilience-focused partnerships directed toward greater wins are vital, yet—just as in particular communities, or on defined technology—failures can be as, if not more, insightful than successes. Specifically, in policy-making processes, partnerships among infrastructure, technology, and service-providing sectors need clear goals for resilience (alongside efficiency, productivity, safety, etc.) to avert counterproductive actions despite incomplete know-how. Similarly, adopting guiding principles tailored to resilience as part of a broader responsible-innovation framework can help industry avoid risks such as potential disasters, social-reject reactions, and rise-sustainability paradoxes.

But one-off social-buy actions in industry are often insufficient to assuage concerns; smooth acceptance and support of project proposals are best achieved through enduring, equitable sharing of relevant information, leading to responsibility towards microstakeholders and regarding neighbouring macro-environmental areas. In short, scaling these principles can help collaborative actions and public sector-making systems address and build resilience together alongside efficiency, safety, productivity, costs, etc. Finally, the academia perspective is cumulative support through sector-coupling physical models and monitoring services, data democratization and sharing, interdisciplinary efforts, and contribution to long-term research worker-seeding processes. Unlike frontier technologies—and sometimes in opposition—the core concept and geo-environmental conditions may rapidly converge toward resilience but can also divert so as to require necessary further-redirection efforts toward resilience.

7. Chapter Five: Risks, Ethics, and Stewardship

As engineers, scientists, and technologists advance innovations to support environmental resilience, they assume moral obligations toward the world and its inhabitants. (Byskov et al., 2021) Minimizing risk, ensuring accountability, and anticipating unintended consequences constitute responsible innovation. Climate extremes amplify hazards, shifting the risk landscape, with equity implications. Access to power, information, and decision-making channels shapes resilience-building opportunities. Conducting equity assessments alongside technical evaluations promotes equitable resilience.

7. 1. Subchapter: Responsible Innovation

Environmental resilience strategies—deployed technologies, activated communities, and accelerated solutions—plot navigational courses through disruptions, threats, and opportunities. Yet, these activities cannot be utterly free of negative impacts or social risks, nor can they offer effective paths for every affected population or ecosystem. Despite the merits of good research, bad data can creep into models, sometimes causing misleading conclusions that bias decisions. Moreover, even though such decisions will reflect an evolving understanding of uncertainty, a cautious heat wave or storm will still likely stress suboptimal solutions, revealing real-world vulnerabilities. Public outrage may follow, however unjustly, thereby forcing the policy process into reactive mode. Here, the engine of innovation is not inventors in labs but rather humans at the steering wheel, cutting across compartments to set future directions and enhance public safety.

Because the risks of innovation seldom fall equally on every part of society, it is also important to consider issues of justice and equity, with a view to creating a resilient future for all. The impacts of a degraded environment are borne most heavily by socially vulnerable groups—those, for example, without access to health care, income and food security, adequate housing, or transport and communications systems—and special effort is needed to incorporate their needs and perspectives into environmental resilience preparations. Quantifying the potential gains and losses of proposed strategies thus calls for engaging local communities, stakeholders, and the broader public, ideally guiding future efforts toward solutions that lower the vulnerability of all.

7.2. Subchapter: Equity in Resilience

Like water permeating sediment, equity infuses resilience at every level and in every aspect of its definition, from the framing and design of projects, studies, and policies to the dissemination of knowledge, the establishment of planning agendas, the realization of project benefits, and the participation in technical discussions and decision-making. Failure to deal with equity—whether intentionally or inadvertently—can short-circuit the innovation required for resilience and undercut society’s capacity for change across the many dividing lines that now exist, including: urban and rural; human-built and natural; and public, private, and civil sectors (Tripati et al., 2024). It is helpful to think initially in terms of the basic dimensions of equity—distributive, procedural, and restorative—briefly reviewing the contemporary discourse surrounding them and then exploring specific manifestations within the context of resilience.

8. Epilogue: A Future We Choose

The best available science indicates that evasive planetary changes are already well underway and that the consequences will continue to intensify for decades, producing unprecedented societal upheaval with profound implications for human well-being, ecosystems, and entire generations, while humanity nevertheless retains the profound agency to select options that yield a radically different trajectory toward a thriving future characterized by just, diverse, planetary-scale innovation and fundamental transformations of the economy, technology, governance, and values to firmly prioritize resilience, justice, democracy, and well-being through co-creation among natural and social scientists, engineers, designers, technologists, humanists, artists, policymakers, practitioners, and the public (M Bennett et al., 2021).

Conclusion

To navigate an increasingly turbulent world, scientific and engineering efforts must coalesce around guiding principles, frameworks, and tools to strengthen the resilience of the interdependent systems shaping people's lives; three broad themes emerge: an innovation mindset that embraces experimentation and co-creation with communities, a commitment to rigorous data practices that clarify risks and opportunities, and an understanding of environmental and socio-technical systems that illuminates approaches for advancing resilience. (M. Murray et al., 2013)

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