



RADemics

# Mathematical Modeling and Simulation for Health, Energy, and Climate Systems



Vijay Kumar Dwivedi, S. Muthurajan

GOVERNMENT ENGINEERING COLLEGE AMBIKAPUR, DEEMED TO  
BE UNIVERSITY

# Mathematical Modeling and Simulation for Health, Energy, and Climate Systems

<sup>1</sup>Vijay Kumar Dwivedi, Assistant Professor, Department of Mathematics, Government Engineering College Ambikapur, Chhattisgarh, India. [dwivedi.vk69@gmail.com](mailto:dwivedi.vk69@gmail.com)

<sup>2</sup>S. Muthurajan, Assistant Professor, Department of Marine Engineering, Academy of Maritime Education and Training (AMET), Deemed to be University, ECR, Chennai, Tamil Nadu, India. [smuthuraajan@gmail.com](mailto:smuthuraajan@gmail.com)

## Abstract

Accelerating climate variability, rising energy transitions, and increasing public health pressures have intensified the need for unified analytical frameworks capable of capturing cross-sectoral dynamics. Mathematical modeling and simulation provide a rigorous foundation for analyzing nonlinear interactions, feedback mechanisms, and cascading risks across interconnected health, energy, and climate systems. This chapter develops an integrated system-of-systems modeling architecture that combines deterministic and stochastic differential equations, optimization theory, uncertainty quantification, and hybrid artificial intelligence–physics approaches within a coherent computational framework. Stability analysis, bifurcation theory, and sensitivity assessment are embedded to identify tipping thresholds and resilience margins under compound stress scenarios such as extreme weather events, infrastructure disruption, and epidemiological surges. Climate-constrained energy optimization and predictive health infrastructure modeling are linked through probabilistic uncertainty propagation, enabling robust scenario evaluation and risk-informed decision support. The proposed framework further incorporates digital twin architectures and explainable artificial intelligence to enhance transparency, interpretability, and policy relevance of multi-domain simulations. By bridging traditionally isolated modeling paradigms, this contribution advances methodological foundations for sustainable planning, adaptive governance, and resilience engineering within complex socio-environmental systems.

**Keywords:** Mathematical Modeling; System-of-Systems Simulation; Uncertainty Quantification; Hybrid AI–Physics Modeling; Climate-Constrained Energy Optimization; Health Infrastructure Resilience.

## Introduction

Escalating climate variability, accelerating energy transitions, and increasing public health vulnerabilities have intensified global concern regarding systemic resilience across interconnected infrastructures. Complex interactions among atmospheric processes, energy production systems, and healthcare networks generate nonlinear behaviors that challenge conventional analytical approaches. Temperature extremes alter electricity consumption patterns, energy supply disruptions influence hospital functionality, and environmental degradation shapes disease transmission dynamics. Such interdependencies reveal the necessity for integrative mathematical frameworks capable of capturing cross-domain feedback loops and cascading effects. Traditional

sector-specific models offer valuable insights within isolated boundaries, yet fragmentation limits the capacity to anticipate compound risks arising from simultaneous stressors. A comprehensive modeling perspective grounded in applied mathematics and computational simulation enables structured representation of dynamic interactions across scales, from local infrastructure performance to global climatic trends [1–4].

Mathematical modeling provides the theoretical architecture for representing evolution of state variables governing health, energy, and climate systems. Differential equations, stochastic processes, and optimization formulations describe temporal progression, spatial diffusion, and constrained resource allocation within complex networks [5–8]. Nonlinear dynamics frequently emerge from feedback mechanisms linking emission trajectories, energy demand, and epidemiological spread. Stability theory, bifurcation analysis, and sensitivity assessment facilitate exploration of equilibrium behavior and regime transitions under parameter variation [9–12]. High-dimensional modeling structures accommodate multi-scale coupling, integrating atmospheric circulation outputs with regional load forecasting and healthcare capacity planning. Computational advances in numerical solvers and high-performance computing environments enable simulation of coupled systems with increasing resolution and predictive depth [13–15].

Energy system transformation toward low-carbon pathways introduces additional layers of complexity within climate-sensitive contexts. Renewable integration, storage deployment, and carbon mitigation strategies influence operational stability and economic feasibility of power networks [16–18]. Climatic variability modifies renewable resource availability while shaping consumption intensity through heating and cooling requirements. Optimization frameworks incorporating emission constraints and reliability thresholds support evaluation of adaptive dispatch strategies under uncertain environmental forcing [19–21]. Simulation-based scenario analysis quantifies trade-offs between sustainability targets and infrastructure resilience. Coupled modeling of generation assets, transmission networks, and demand-side responses strengthens understanding of systemic vulnerabilities linked to extreme weather events and long-term climate shifts [22–24].