Chapter 5
Hydrogen Supply Chain Effectiveness: Conceptualizing Uncertainties Through Genetic Simulations

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ABSTRACT

The shift from carbonaceous sources to cleaner alternatives necessitates reorienting and optimizing energy supply chains. Despite technological advancements, energy security remains susceptible to disruptions caused by geopolitical tensions, resource constraints, and market fluctuations. This chapter explores how genetic simulations, leveraging metaheuristic optimization techniques, facilitate a trade-off between the resilience and cost-effectiveness of green hydrogen supply chains. A data-driven case study examines the first-level viability of the envisaged green hydrogen system, covering prominent pathways for production, storage, and transportation and

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distribution (T&D). Scenarios are ranked based on cost per tonne for production, storage, and T&D. Prima facie viable cases are further discussed considering supply chain vulnerability under geopolitical and logistical constraints. Such studies help strategize long-term energy security for developing economies like India.

1. INTRODUCTION

The modernization of the world is built on key socio-structural changes, which have been gaining momentum since the beginning of the 21st century. Some of the principal changes include a rapid increase in population accompanied by the growth of industries, marked by increased energy consumption levels. Global energy demand increased by more than 2% to 642 EJ in 2023 on a year-on-year basis (International Energy Agency, 2024). This increase is attributable to developing countries that more than offset the declining demand profiles of advanced countries.

For a long time, energy was considered the intrinsic driver of economic growth in any region. However, despite its paramount importance, a broad presumption existed in the first half of the 20th century regarding an infinite supply of affordable energy. This assumption indeed lacked foresight and was devoid of sustainability thinking. Emerging supply-side constraints in the energy sector forced experts and decision-makers to consider energy-related policy formulation seriously (Banks, 2012). In the 21st century, the global focus progressively shifted from 'growth-driven development' to a more holistic approach encompassing a wider gamut of trans-disciplinary factors like environmental impact, affordability, sustainability, etc., eventually leading to a gradual shift toward energy mix diversification. Diversification of energy sources was also important from the local and regional energy security point of view, considering multiple phases of major geopolitical volatilities worldwide.

In an evolving energy landscape aspiring for 'green transition' at scale, it is crucial to maneuver away from energy generation pathways that rely heavily on carbonaceous fossil fuels, leading to a significant increase in greenhouse gas (GHG) emissions. Fossil fuels are not uniformly distributed globally, and regional concentration of resources often creates uncertainties regarding the availability and accessibility of energy currencies (energy forms ready for end use). Fluctuations in the energy markets (price volatility), disruptions in supply chains, and trade policies of different advanced nations have historically impacted the reliability of uninterrupted energy supply and the sustenance of socio-economic development. The oblique dependency on hydrocarbon-based fuels has serious repercussions on the climate, ecology, health, and energy security, forcing many nations across the globe to adopt climate-resilience measures, including lifestyle adaptations (Castro & Sen, 2022).

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