

Views & Comments

Promoting Global Energy System Transformation Toward Carbon Neutrality: A Four-Stage Pathway of System Integration



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1. Introduction

The global energy landscape has undergone profound changes since the industrial revolution, characterized by three major shifts in primary energy sources [1]. These include the transition from biomass to coal between 1850 and 1950, followed by the shift from coal to oil from 1950 to 2000, and the more recent move toward a diversified energy structure at the beginning of the 21st century. Each shift was driven by visible crises—deforestation, air pollution, and oil supply disruptions—and the competitiveness of new technologies [2,3]. Currently, achieving carbon neutrality by 2050–2070 has become a global policy target, with 151 countries committed to national carbon neutrality goals by May 2024 [4]. In this context, energy system transformation (EST), also referred to as energy transition, has become a central concept representing the urgent need for radical structural changes in energy systems within a relatively short timeframe. Specifically, primary energy sources and carriers must predominantly derive from renewable energy and electricity, with an accelerated shift away from fossil fuels [5]. However, EST toward carbon neutrality presents a significantly more complex challenge. Academic discussions on EST have become increasingly popular in recent years. An early example is that Steve Rayner concluded *energy system must be recognized to be as much a social system as it is a technical one* after discussions of climate science and policy in his paper published in 2010 [6].

Unlike past energy shifts, EST toward carbon neutrality faces the dual challenges of insufficient public awareness regarding climate urgency [7] and incomplete market readiness for innovative technologies that enable the high penetration of renewables, such as power storage, demand-side response, distributed energy systems, and green hydrogen [8,9]. Unlike previous crises, climate change does not pose an immediate or tangible threat, making public awareness and actions more gradual. Furthermore, renewables, including wind power and solar photovoltaics, when integrated into energy systems, have not reduced the consumption of fossil fuels. This is because they require many enabling technologies that still lack market competitiveness, that in turn, leads to greater reliance on the economy and flexibility of fossil fuels. Con-

sequently, achieving EST toward carbon neutrality requires more than technological advancements or policy interventions, necessitating a broader energy-societal paradigm shift. Without the traditional driving factors, this paradigm shift requires significant political, economic, industrial, and societal changes. It must be approached as a complex sociotechnical system in which shifts in public consciousness, governance structures, and operational models are equally important as technological innovation. Additionally, the integration of conventional and emerging energy systems is crucial to minimize disruptions in the pursuit of a higher quality of life in the society.

Acknowledging the need for a comprehensive integration of energy and societal systems, this study proposes a practical and sustainable pathway for energy-societal system integration in EST toward carbon neutrality. It also offers recommendations for immediate actions that leading experts and policymakers from major countries can undertake, grounded in systems theory, particularly systems engineering principles. In the following sections, we outline a four-stage pathway for energy system integration to achieve global carbon neutrality. We advocate an interdisciplinary approach to catalyze this pathway through international cooperative research and practice.

2. Four-stage pathway of system integration in EST toward carbon neutrality

Achieving carbon neutrality is not simply a matter of reducing carbon emissions; it is about fostering sustainable development across all facets of society that requires a profound rethinking of the current narratives. EST cannot be achieved through an isolated focus on a limited set of technologies. Instead, a harmonious integration of existing and emerging technologies is required. The key to this integration lies in energy-societal systems thinking that demands a multidisciplinary approach to the design, optimization, and management of energy systems.

From a systems engineering perspective, the problem is clear: we must continuously innovate and deploy new technologies to ensure a dynamic evolution from the current high-carbon energy system to a future energy system characterized by zero or even negative emissions. The economic burden posed by the high costs of low-carbon technologies is further complicated by significant

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conflicts of interest with existing fossil fuel-based systems. These conflicts must be addressed for the EST to be successful.

Given these complexities, the following guideline is proposed to determine the pathway toward EST.

Realize global carbon neutrality as early as possible, while promoting sustainable development for the entire humanity, including:

- Satisfying basic demands of various countries while encouraging international cooperation.
- Accelerating technological breakthroughs in low-carbon technologies across supply chains.
- Advancing human civilization toward a prosperous and harmonious world under carbon-neutral conditions.

This guideline emphasizes the importance of a holistic, coordinated, and incentive/penalty-driven approach that unites stakeholders across regions and sectors, ensuring that the EST pathway is both technically feasible and socially acceptable.

Based on this guideline, we propose a four-stage pathway, as shown in Fig. 1. The left and middle sections of the figure (in black and blue, respectively) illustrate the historical trend of energy-related carbon emissions [10], energy shifts, and carbon reduction targets aiming for a global temperature rise of 1.5 and 2.0 °C, as outlined by the Intergovernmental Panel on Climate Change (IPCC) [11]. The right section (in green) presents the four-stage pathway for system integration in EST toward carbon neutrality, guiding global efforts from a resource-based past to a sustainable, techno-centric energy future. Notably, the timeframe of these stages is only an approximate estimate and the specific time may vary dynamically.

Stage 1 (2025–2035). This phase focuses on electrifying the multi-energy era by establishing smart grids that integrate centralized and distributed energy sources. Renewable technologies such as wind and solar will scale up, and advancements in energy storage and demand-side responses will address intermittency. Smart grid technologies including early attempts at artificial intelligence (AI), such as using AI to forecast climate conditions, predict potential responses of the society, and manage distributed energy systems and public engagement, will be key to enabling the transition, setting the foundation for a more integrated energy system and completing the Third Industrial Revolution.

Stage 2 (2035–2045). The second stage expands smart grids into smart energy systems, integrating grids with heating and fuel networks [12]. Technological innovations in hydrogen and low-carbon

heating technologies will assume prominence. Cross-sector collaboration is critical for decarbonizing industries, with green hydrogen or hydrogen-derived fuels playing a key role in replacing fossil fuels in sectors such as chemicals, heavy industries, transportation, and power generation. This stage marks the beginning of the Fourth Industrial Revolution, with energy innovations driving breakthroughs. At this stage, AI technology that is capable of managing the entire energy system, making it really smart, must mature.

Stage 3 (2045–2070). This phase focuses on creating ecological energy systems to address environmental and resource limitations. Biomass energy, negative emission technologies, and resource recycling will foster a circular economy by integrating energy systems with natural cycles. The aim is to harmonize energy production and consumption with ecological sustainability to ensure that resource use does not exceed planetary boundaries. This addresses climate change and also promotes resilience against resource depletion and ecological collapse. For instance, the significant consumption of scarce metals driven by EST, along with the potential environmental crises caused by metal mining and processing [13], is expected to be mitigated at this stage. The creation of an ecological civilization will gradually replace industrial civilization that must be phased out because of its inherent ecological damage and depletion of natural resources. At this stage, AI technology must establish connections between human society and ecosystems, integrate more knowledge about the mysteries of nature, and move toward a more advanced stage.

Stage 4 (beyond 2070). The future will witness humanity exploring new energy technologies, particularly nuclear fusion, that can provide limitless clean energy. At present, nuclear fusion can be achieved but is difficult to control. The energy obtained is typically offset by the energy that controls it and operating under controllable conditions for a long time is difficult. Although international scientific cooperation programs, such as international thermonuclear experimental reactor, are already available, the expected commercialization time is often delayed. Considering the commercialization difficulties of controllable nuclear fusion on Earth, we placed nuclear fusion at this stage. Although technological problems are difficult to overcome without the unity of the entire human society, this is currently a science and technical issue rather than an international cooperation issue. The imagined realization of fusion energy will mark a new era of energy abundance, enabling further space exploration and potential colonization of

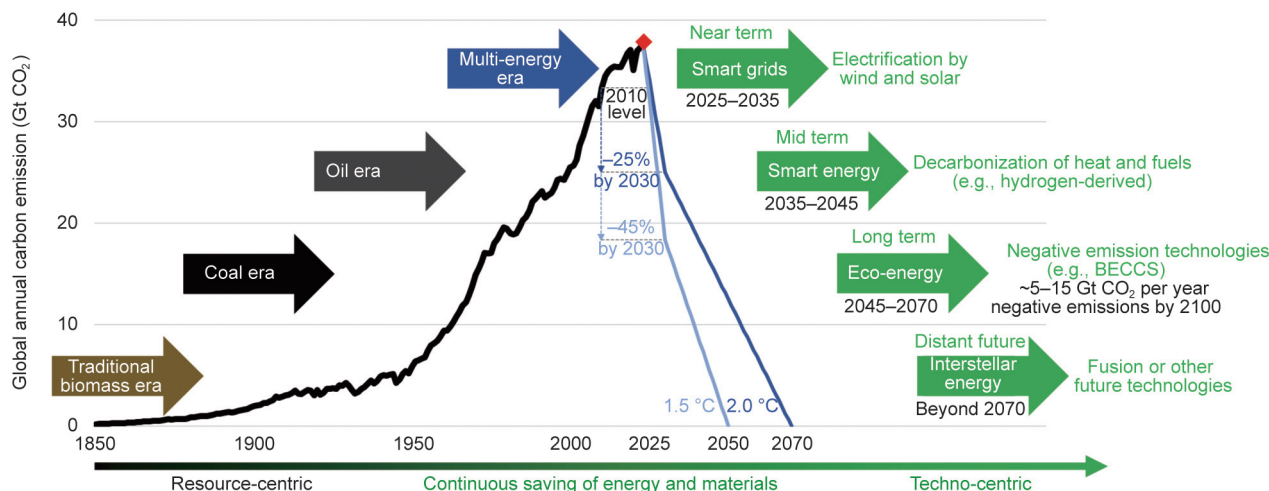


Fig. 1. Historical energy-related carbon emissions and four-stages of system integration. BECCS: bio-energy with carbon capture and storage.

other planets. This bold vision can leap technological innovation and reshape human civilization to a civilization that expands possibilities beyond Earth. AI is also expected to replace humans in testing early interstellar navigation and continuously assist humans in real navigation based on experience and massive calculations.

To this end, the proposed four-stage pathway for EST toward carbon neutrality offers a comprehensive framework that embraces the principles of system integration, global cooperation, and the continuous innovation of human civilization. Of the aforementioned four stages, Stages 1 and 2 are basically the current consensus of authoritative institutions in the energy field, such as the International Energy Agency and Energy Transitions Commissions [14]. Stages 3 and 4 are mainly hypotheses constructed by the author based on energy-societal system thinking.

International cooperation requires the establishment of various mechanisms at different developmental stages. In the smart grid stage, as the major countries establish their own smart grids, mechanisms such as technology innovation alliances, technology trade agreements, and technology pathway consensus are required, particularly among industrialized countries. In the smart energy systems stage, large-scale international trade brought about by hydrogen or hydrogen-derived energy will create a demand for an innovative international green energy trade agreement, requiring the reshaping of the international energy trading system. In the ecological energy system stage, we expect the concept of the nation to become blurred and cooperation between different communities in various ecosystems to become more important. Interstellar energy inevitably relies on a union of the entire human society, and this problem may change into star-level cooperation.

3. T-ESGO approach integrating four types of flows through three “i” drivers

A preliminary review [14] identified critical gaps across energy system modeling, sustainability frameworks, governance structures, and societal operations as they relate to EST toward carbon neutrality. These gaps are particularly evident in the coordination of multidimensional flows—energy, materials, and carbon emissions—and in the interdisciplinary approaches required to address these challenges. Although theoretical advancements in these domains are essential, the slow evolution of these frameworks has been insufficient to address the urgency of the global sustainability crisis. Instead, a “learning-by-doing” approach (that is, to accumulate experiences through practices and then achieve knowledge growth from experiences) is necessary to accelerate the integration of diverse technologies, policies, and governance structures. This approach requires real-world experiments and iterative improvements while simultaneously establishing robust theoretical foundations.

As illustrated in Fig. 2, we propose a Trinity-guided energy systems, sustainability, governance, and operation (T-ESGO) framework to foster a resilient and inclusive society that ensures a green and sustainable future. This holistic framework, which is updated from the previous ESGO framework [15], is centered on the integration of experts, models, and data in a specific society, herein referred to as the Trinity. In contrast to other theoretical frameworks, the T-ESGO approach places primary emphasis on continuous learning and practical implementation, establishing networked organizations designed to reshape society. Analogous to the function of a gyroscope, the Trinity serves as the central axis, whose neutrality and strength are crucial for the stable and dynamic operation of the entire system. In practice, this represents the formation of just and intelligent organizations staffed by the

foremost experts, models, and data whose collective insights will continually inform the future direction and decision-making of the society.

Fig. 2(a) underscores the mission of these organizations: the integration of four types of flows—energy, materials, carbon, and information. The key to managing carbon emissions lies in optimizing the interconnected energy and material flows that is achieved through a tighter coupling of energy supply with energy demand and a more integrated flow of materials alongside energy. Industries with high energy demands (for example, steel, cement, and chemicals) and those involved in the production of critical minerals (for example, lithium, cobalt, nickel, copper, and rare earth elements) must optimize their energy usage in tandem with material production. However, the current challenge is that the interplay of energy and material flows exacerbates carbon emissions, disrupting the sustainable development of global society.

As established by information theory, reducing systemic chaos requires enhanced information input. Unlike energy and material flows, information flows are inherently complex and difficult to manage. We propose that information flows can be categorized into four main types: technological, natural, social, and digital. Previous energy system modeling efforts have indicated that EST requires new technologies based on the information generated through technological sciences. However, real-world implementations have demonstrated that reliance on technology alone is insufficient. Insights from natural and social sciences are crucial because they provide a deeper understanding of the laws governing nature and society that can aid in addressing systemic challenges. Furthermore, the exponential growth of data necessitates the application of data science to process and extract value from these vast datasets; without this, the data itself becomes chaotic.

In summary, the problem stems from the evolution of energy and material flows, whereas the solution lies in the optimization of information flows. The chaos induced by carbon emissions is mitigated through the continuous iterative cycles of the T-ESGO approach. Consequently, the core focus of the Trinity is to address the carbon emission challenges arising from energy and material flows and to integrate expertise, models, and data from disciplines spanning carbon flow monitoring and energy technology development as well as natural, social, and information sciences. This integrative process enables continuous analysis and system-wide integration across societal sectors. Advancements in information science and technology, such as AI, enable faster integration of diverse information flows. AI can increase the speed of discovering and applying laws in various scientific fields, strengthen the effectiveness of scientific communication and interoperability between different disciplines, and continuously integrate expert knowledge into technologies to optimize energy systems. AI cannot develop solely in the field of information science but must be combined with expert knowledge from other scientific fields to achieve more energy-efficient and management-effective technologies.

Fig. 2(b) highlights three primary drivers of the Trinity approach: innovation, interdisciplinary, and international cooperation, collectively referred to as the three “i” drivers. These capabilities are essential for maintaining the neutrality and strength of the Trinity axis, ensuring rapid functioning and ongoing renewal of the societal system through self-organization. In regions where these capabilities are underdeveloped, the formation of a Trinity framework requires substantial capacity building. Nevertheless, any early efforts to advance the Trinity will catalyze faster development and diffusion of these key capabilities. The IPCC is a successful example of the Trinity that integrates experts, models, and data from multiple countries to innovate scientific reviews and effectively inform decision makers, helping to advance global climate governance. However, currently, in the fields of international trade and technological innovation related to EST, this Trinity is lacking.

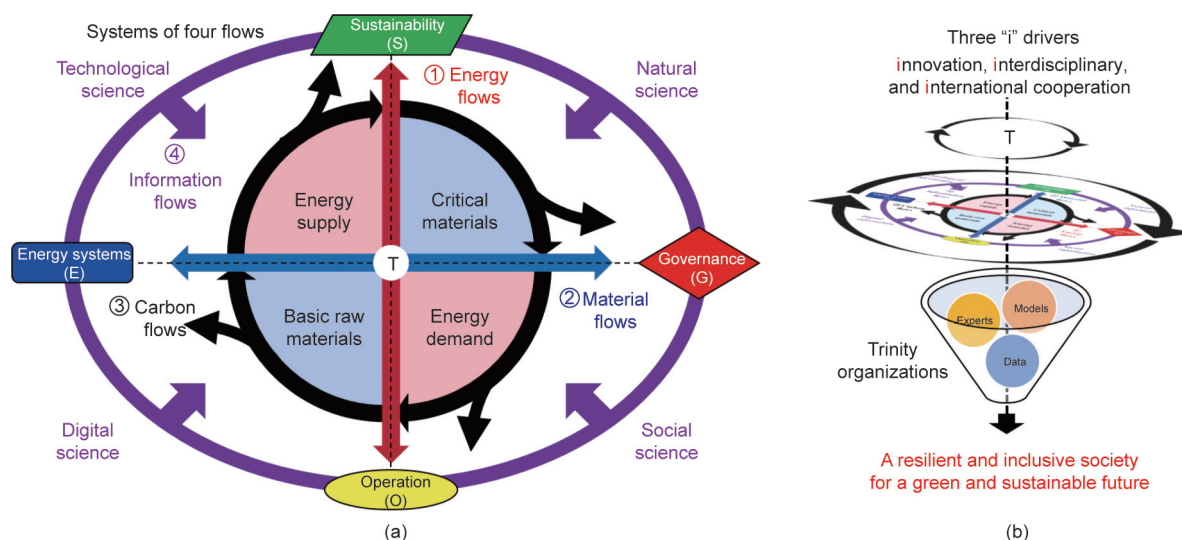


Fig. 2. A T-ESGO approach integrating four kinds of flows through three “i” drivers. (a) A system description of four kinds of flows by ESGO approach; (b) Trinity organizations driven by innovation, interdisciplinary, and international cooperation. T: Trinity.

If certain countries mastering “learn-by-doing” to achieve high development and innovation speed, such as China, can initiate and promote international cooperation, then international cooperation on EST can be improved and accelerated. On June 27–29, 2025, Tsinghua University officially launched the Carbon Neutrality and EST (CNEST) International Multilateral Cooperation Project in Beijing to promote the disruptive technological innovation of EST by international cooperation; this is exactly an attempt in this regard. The disruptive innovation proposed by CNEST includes global carbon monitoring networks, new energy infrastructure based on smart grids, intelligent interconnection technology for energy systems, innovative low/zero/negative carbon technologies, and digital twins for energy systems. The systematics of EST is also proposed as a guiding theory for these technological innovations.

4. Conclusions

Achieving carbon neutrality involves significant challenges, including fragmented efforts, insufficient public awareness, and uncompetitive low-carbon technologies. This study proposes a four-stage system integration pathway—from smart grids and smart energy systems to ecological and interstellar energy systems—rooted in systems thinking and technological progress. To facilitate this transition, the T-ESGO framework emphasizes the integration of energy, materials, carbon, and information flows. Innovation, interdisciplinary, and international cooperation are essential for success. Despite future uncertainties, we remain optimistic about the potential of science and societal renewal to overcome these challenges and advance energy system integration.

CRedit authorship contribution statement

Linwei Ma: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Maximilian Arras:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Project administration, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the first author (Chinese) used an online Baidu language translation service to more efficiently translate certain Chinese text into English. Subsequently, the authors reviewed and edited the content as needed. The authors take full responsibility for the content of the publication.

Acknowledgments

This research was funded by the Carbon Neutrality and Energy System Transformation (CNEST) Program and the Major Program of the National Social Science Foundation of China (21&ZD133). We are also grateful to Professors Kebin He, Zheng Li, and Xi Lu of Tsinghua University for their insightful guidance and constructive feedback throughout the study.

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