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Views & Comments

Optimizing the Roadmap to Carbon Neutrality with a New Paradigm

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1. Introduction

Formulating an optimal roadmap to realizing the goals of peak carbon dioxide emissions and carbon neutrality calls for a systemic analysis of mesoscale structures at multiple levels and of their governing multi-objective mechanisms within different sectors and fields. However, the analyses currently available are mostly based on traditional approaches, which have not considered different levels of complexity and heterogeneity sufficiently, or have not accounted for multiple objectives sufficiently reasonably. In this perspective article, we attempt to figure out a new framework for dealing with this challenging issue within a totally different paradigm for multiscale complex systems, in which such a global challenge and the paradigm shift in science need to be addressed jointly.

2. Key scientific issues related to the challenge

Realizing carbon neutrality and energy revolution (e.g., that proposed in China [1]) requires a reliable, scientific, and rational energy strategy. This involves the restructuring of the energy and industrial sectors, which is a very complex systemic issue that concerns not only the modeling of the system, but also the development of corresponding standard systems based on the model framework. Therefore, it is impossible to achieve global change goals without joint global actions—or, more importantly, without the global coordination of diverse strategies. No single country can achieve the goals on its own; therefore, coordinated action is a necessity in order to efficiently accomplish the involved challenging tasks. Formulating such strategies requires systems thinking, which can also be regarded as a specific case of a paradigm shift in scientific research.

The reliability and accessibility of an energy strategy depend on the data and models of energy sectors, which are subject to industrial and social factors. However, the prevailing energy models (including top-down models, bottom-up models, and hybrid models) are not yet perfect [2] and need to be upgraded within the framework of a new paradigm. Data must be further collected and sorted within the same framework as well.

In terms of models, top-down models are typically based on the general equilibrium theory [3]; they ignore dynamic heterogeneity (e.g., the structures of inputs, allocations, and regions) and use averaging parameters, which can lead to substantial deviations from reality. Bottom-up models are based on the partial equilibrium theory, in which the economy is exogenous and policy constraints are difficult to introduce. The cost involved is generally limited to the technological cost, and the usually adopted single-objective optimization of cost minimization is impractical and can lead to unreasonable flip-flop results [2]. Moreover, the formidable computational cost involved makes it difficult to apply these models to large-scale scenarios. Hybrid models are simple combinations of top-down ones and bottom-up ones, without introducing the necessary mechanisms and thus failing to fundamentally eliminate the aforementioned defects.

In terms of data, the primary data are usually ponderous and scattered, essentially due to the effects of heterogeneous factors, and are thus difficult to apply directly and effectively. Therefore, the primary data must be sorted out and integrated into secondary or higher-level data.

A breakthrough is urgently needed to solve these problems for such complex giant systems with boundary conditions involving the accessibility of resources, the affordability, and the limitations posed by ecological and climate goals. Making such a breakthrough requires a paradigm shift in scientific research to overcome the difficulties posed by the involved spatiotemporal complex structures. Therefore, the key to addressing such a major challenge lies in building complex-system models and corresponding standard systems.

At present, the goals of peak carbon dioxide emissions and carbon neutrality are clear, and it is urgent to break through the limitations of existing energy models, establish accurate and efficient energy-system models, develop efficient solvers, and build dynamic databases at all levels. Only by fulfilling these tasks can energy strategy research be strongly supported. This is the most urgent mission now.

3. Establishing complex-system models and corresponding standard systems based on a new paradigm of complexity

Research on energy strategy for a specific region or beyond involves at least three correlated levels: the unit-technology level, the technology-chain level, and the regional-or-above level. Each level has three typical scales: the unit scale, the system scale, and the in-between mesoscale. Understanding and regulating the complex mesoscale structures at these levels is the key to optimizing, designing, and predicting the system behavior. Mesoscale behavior

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is essentially a reflection of the compromise in competition between different dominant mechanisms, and also corresponds to a multi-objective optimization or variational problem [4].

The most critical and also the most difficult to deal with is the technology-chain level—a key level that is not well addressed by currently available models. At this level, the unit scale is the scale of the unit technology, the system scale is the scale of the whole technology chain, and the mesoscale is the in-between scale at which complex technology-chain structures exist. The technology-chain structure is a network of conversions between different energy species through different energy technologies. At this level, the inputs of the system are energy or resources supply, available technologies, capital, and economic, environmental, and social indicators. The outputs are energy of demand and the byproducts of energy conversion. Preliminary studies indicate that the two competing dominant mechanisms that govern the mesoscale behavior at this level are energy saving and energy-loss reduction, versus cost saving and emission reduction. The first mechanism of energy saving and energy-loss reduction takes the energy-conversion route with the maximum cumulative energy efficiency to produce the maximum amount of demanded energy with the minimum amount of supplied energy or resources. The cost-saving and emission-reduction mechanism takes the energy-conversion route with the minimum cumulative cost and emissions. The compromise of these two competing dominant mechanisms leads to the complex structure of the actual energy technology chain. Accordingly, the energy industry can be structurally optimized under the new paradigm.

The unit-technology level comprises scales that are adjacent to and smaller than those of the technology-chain level, with the system of the former level being the unit of the latter level—namely, the unit technology of energy conversion. At the technology-chain level, the unit technology is a single route with definite technical parameters. At the unit-technology level, the unit-technology system includes all possible processing routes corresponding to a large number of different technical parameters. The unit of this level is any possible processing route. The mesoscale structure is the spatiotemporal distribution of the applied magnitudes of different processing routes for each unit technology. Based on the compromise in competition between corresponding dominant mechanisms (currently under exploration), it is expected that definite technical-parameter values will be derived and can be used subsequently at the technology-chain level. For example, the technology-chain level adopts technical parameters such as the cost, emissions, and efficiency of each technique. It is preferable to achieve the definite values of such parameters through the corresponding multi-objective optimization that reflects the compromise between the competing mechanisms governing the spatiotemporal magnitude distribution of different routes. Taking an instantaneous or local value, or the simple average of different routes, will make no sense. This is common in various complex systems.

The region-or-above level comprises scales that are adjacent to and larger than those of the technology-chain level, with the unit of the former level being the system of the latter level—namely, the whole technology chain within a certain sector in a certain economic and social region. The system at this level is the collection of multiple technology-chain assemblies. Its input and output form the energy flow and substance (including carbon) flow in the corresponding region. Its constraints are economic, environmental, climate, and social indicators. The mesoscale structure at this level is the connection of different technology-chain assemblies. The multi-objective optimization results obtained based on the compromise in competition between the dominant mechanisms (hopefully to be identified in the near future) governing the mesoscale structure of this level are expected to directly guide the energy development planning of the corresponding region. Beyond regions, more levels might exist, such as the country level, the continent level and, finally, the global level—the actual discrimination is certainly subject to specific economic and social relationships.

In regard to the design of standard systems, the aforementioned three or more levels should be accounted for as well. First, we should establish models at these levels, such as models of unit technologies, of industrial structures, and of regions. Subsequently, these levels should be correlated to form a comprehensive multilevel and multiscale structured model of the whole system, and boundary conditions should be introduced. Standards should be developed accordingly for each level and also for the whole system in order to facilitate systemic analysis. That is to say, it is only based on corresponding models that we can develop a targeted standard system and a systemic basis for policy. Consequently, the overall energy system (related to the industrial system) can be quantitatively analyzed and regulated.

To sum up, it is expected that revealing the dominant mechanisms governing the mesoscale structure at each level, as well as their competition and compromise relations, and establishing the correlations between different levels will develop effective new energy models and multilevel data systems. Along with the development of relevant solvers, a completely new method for energy strategy research will be developed to support the planning and deployment of the energy revolution in a region, a country and, eventually, the whole globe. This method will also play a significant guiding role in the design of technology routes and the formulation of standards for peak carbon dioxide emissions and carbon neutrality, by offering optimal solutions to multi-objective problems and (hopefully) helping to avoid mistakes in route selection. Such a paradigm might also work for the 17 Sustainable Development Goals proposed by the United Nations [5].

After developing the models for a region, we can further extend them to a country and even to the globe, thereby helping to foster the coordination mechanisms for global strategies. This methodology will be expected to pave a unique path to realize global goals efficiently. Optimizing the roadmap to carbon neutrality is not only a global challenge for the sustainable development of humanity, but also a great scientific issue. Tackling it requires global minds, making open and inclusive cooperation especially important.

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