Reflections on the Evolution of New Quality Productive Forces, Renewable Energy, and Territorial Spatial Planning: A Discussion Centered on Wind and Solar Energy

WANG Yizhe, WANG Xingping, ZHU Zhenwei

Abstract. "New quality productive forces" constitute a strategic lever for achieving leapfrog advances in China's productive capacity. Spatial planning should proactively guide the spatial deployment of renewable energy production, particularly wind and solar power, and use energy as a medium through which new quality productive forces can emerge. This paper examines the relationships among productive forces, energy, and space. It argues that renewable energy is a foundational condition for the development of new quality productive forces: historically, qualitative transformations in productivity have repeatedly been accompanied by changes in dominant energy forms. Energy transitions also reshape patterns of land-surface use. Wind and solar power overturn the spatial logic of conventional energy systems and give rise to a new form of land use—"spatial energy production"—that both redefines spatial value and challenges existing systems of land use. On this basis, the paper develops a "productive forces–energy–space" analytical framework. Territorial spatial planning bears an important responsibility for managing energy resources embedded across China's entire territory; however, planning concepts and instruments rooted in the fossil-fuel era are increasingly ill-suited to renewable-energy development. It is therefore necessary to return to the fundamental relationship between energy production and space and to innovate spatial concepts, analytical methods, planning tools, and implementation mechanisms.

Keywords: new quality productive forces; renewable energy; territorial spatial planning; land-surface space; spatial resources; solar energy; wind energy; energy production.
Chinese Library Classification: TU984. Document Code: A. DOI: 10.16361/j.upf.202503006. Article No.: 1000-3363 (2025) 03-0043-09.
* Funded by the Key Project of the National Social Science Fund of China, "Promoting the High-Quality Development of Chinese Overseas Industrial Parks along the Belt and Road" (Project No. 22AZD052), and the Jiangsu Postgraduate Research and Practice Innovation Program, "Low-Carbon Development Pathways, Mechanisms, and Planning Models for Industrial Parks" (Project No. KYCX23_0313).

The world is undergoing changes unseen in a century, and the global order is being profoundly reconfigured. China has adopted "new quality productive forces" as a strategic means of gaining an advantage in comprehensive international competition while promoting productivity upgrading and high-quality development. In recent years, forms of new quality productive forces represented by artificial intelligence, intelligent electric vehicles, and robotics have rapidly entered production and everyday life, driving major advances in science, technology, and the economy. Against this backdrop of accelerated technological change, the role of spatial planning—and the contribution it should make—has become a central concern for both the discipline and the wider profession [1]. Although spatial planning is broadly connected to many fields, its direct object is not technology itself but the external environment in which technology develops and operates. As information science led by artificial intelligence increasingly focuses on virtual-space expansion, spatial planning may appear to be drifting away from the technological frontier.

In fact, the opposite is true. Physical and virtual space are acquiring a new connection through energy. Emerging energy systems represented by wind and solar power are integrating productive forces, energy, and space into an organic whole and are creating a new pathway through which spatial planning can support productivity growth. As early as 2005, Shen Qingji [2] argued that urban planning had an important role in renewable-energy development. More recently, scholars of energy geography and sustainability transitions have further confirmed the theoretical importance of "space" to "energy transition." Matthew Huber [3], Gavin Bridge, and others [4] have all argued that space and land should be placed at the core of any theory of energy transition. Geographers have examined energy, space, power, security, and justice from multiple theoretical perspectives [5-6]. Researchers in architecture and urban planning have explored the relationships between urban form—individual buildings, building groups, and entire cities—and renewable-energy production [7-8], while others have focused on how spatial planning should respond to climate change [9]. Yet comparatively little research has examined how spatial planning should respond from the combined perspective of energy and space.

As the world's largest promoter of renewable-energy transition, China has recently established territorial spatial planning as a new and powerful spatial governance instrument [10-11]. How is this instrument related to the ongoing energy transition and the development of new quality productive forces? What role can it play? Reflecting on these questions is important to the construction of a modern Chinese planning theory [12]. Many scholars have already examined the broad and varied relationships between new quality productive forces and spatial planning [13]. Taking energy as the mediating variable, this paper focuses on two sets of relationships—productive forces and energy, and energy and land-surface use—develops a "productive forces–energy–space" analytical framework, and clarifies the role, current limitations, and future directions of territorial spatial planning in renewable-energy transition.

1 "New Quality Productive Forces" and "Renewable Energy"

1.1 Conceptual clarification: the relationship between "productive forces" and "energy"

"Productive forces" are generally defined as humanity's capacity to transform and use nature, whereas "energy" is commonly understood as the "capacity to perform work," applicable across human societies and their interactions with the natural environment [14]. Both concepts describe an abstract capacity for human practice and therefore share closely related meanings. In the 1960s, Soviet astronomer Nikolai Kardashev [15] treated energy as the foundation of the productive development of all civilizations and proposed an index based on the capacity to use energy—the Kardashev scale①—to measure the level of civilizational advancement. When the historical relationship between technological revolutions and energy is taken into account [16], energy may even be understood as a concrete and quantifiable expression of productive capacity.

Growth in the total scale of energy use is an important indicator of social productivity and is closely related to the material prosperity of ordinary people. A middle-class household in a twenty-first-century American suburb may consume energy at an average power level of 30 kW in everyday life, equivalent to the combined work output of 6,000 strong slaves owned by an aristocrat in the Roman Empire [17]. This comparison shows how large-scale modern energy supply allows ordinary people to enjoy living standards far beyond those of ancient elites②. Likewise, China's per-capita energy consumption reached 4,053 kg of standard coal in 2023, 43.6 times the 1953 level of 93 kg. This is one of the most direct expressions of China's rapid modernization of productivity. In this sense, every major leap in productivity has rested on an energy revolution. Although "high energy consumption" is commonly used negatively today, historical experience repeatedly shows that advanced productive tools often entail greater energy use: advanced productivity is supported by high energy consumption.

1.2 Historical experience: "new quality productive forces" rest on "new energy"

Today, "new quality productive forces" is used as a specific term referring to an advanced form of productivity in which innovation plays the leading role, traditional modes of economic growth and established development paths are transcended, and high technology, high efficiency, and high quality accord with the new development philosophy [18]. Historically, however, "new" is always relative to "old," and new quality productive forces are therefore strongly conditioned by their era. The history of human productivity is an iterative process in which each era's "new" productive forces displace the "old." The widespread adoption of the steam engine in the nineteenth century and the diffusion of internal-combustion engines and electrical systems in the twentieth century were both processes through which new productive forces replaced old ones. Coal and petroleum③, respectively, emerged as the “new energy” forms of those eras and were adopted on a large scale [19].

From antiquity to the present, population growth and the pursuit of higher living standards have expanded the scale of energy demand and repeatedly generated new energy forms. Since the eighteenth-century Industrial Revolution, successive waves of coal, petroleum, natural gas, and other “new” energy sources have increased the total amount of energy available to humanity from 5,653 TWh④ to 168,779 TWh [20]—an increase of two orders of magnitude. None of the major collective achievements of human history in agriculture, engineering, industry, or warfare could have been realized without effective energy capture, use, management, and innovation. From the perspective of historical materialism, the development of new quality productive forces objectively creates pressure to expand energy production, while new energy forms provide the firm foundation on which such forces can grow. To some extent, a new energy form is itself a form of new quality productive force.

1.3 Contemporary contradiction: the growth of new quality productive forces is creating an “energy crisis”

Contemporary systems of production are deeply bound to fossil fuels. Intensive fossil-energy use is embedded in almost every social system of modern life, including products, culture, spatial landscapes, and legal institutions [21]. During the Industrial Revolution, fossil fuels appeared as “new energy.” Owing to the thermodynamic advantage of their extremely high energy density, they rapidly dismantled the agricultural social order that had been dominated for millennia by traditional biomass [22]. In The Communist Manifesto, Karl Marx and Friedrich Engels [23] observed that the bourgeoisie had created, within a brief modern period, productive forces exceeding those of all previous generations combined—a transformation supported by the immense material power of fossil fuels. Some scholars have treated fossil-energy use as a foundational condition of the capitalist mode of production and have even coined the term “fossil capitalism” [24]. Yet the environmental externalities of widespread and unrestrained fossil-fuel use—carbon emissions and spatial pollution—are approaching the upper limits of the Earth’s ecological capacity. Low-carbon development is becoming a global trend, while the ceiling of fossil-energy expansion has effectively been fixed and can no longer support exponential growth in future energy use.

At the same time, new technologies represented by artificial intelligence are accelerating the development of new quality productive forces. The evolution of large AI models depends on exponential growth in computing power and data processing, which in turn produces exponential increases in energy use [25]. Research projects that by 2030 global computing capacity may rise by another two orders of magnitude, reaching 5.6×10^{22} floating-point operations per second and consuming an estimated 44.8–67.2 trillion kWh of electricity [26]. This rapidly increasing demand has generated widespread concern. As Elon Musk, founder of Tesla, has argued, the rapid development of artificial intelligence is creating an energy crisis [27]. In January 2025, China’s highly prominent DeepSeek model rapidly entered industries worldwide, enabling new quality productive forces while further raising expectations for computing-related energy demand. The structural conflict between exponentially rising energy demand and the rigid supply ceiling of fossil fuels is therefore becoming increasingly visible.

Wind and solar power are emerging, in both theory and practice, as major solutions to the contradiction between new quality productive forces and the existing energy system. Nearly every part of the Earth’s surface receives intense solar radiation every day, and the total renewable energy available at the surface vastly exceeds current demand—and any plausible future demand. The solar energy reaching the Earth each year is roughly 10,000 times current human fossil-energy use. Wind and solar are widely regarded as the most promising and feasible means of capturing this vast land-surface energy in the foreseeable future [28]. Their development will also generate a profound transformation in how humanity uses the Earth’s surface.

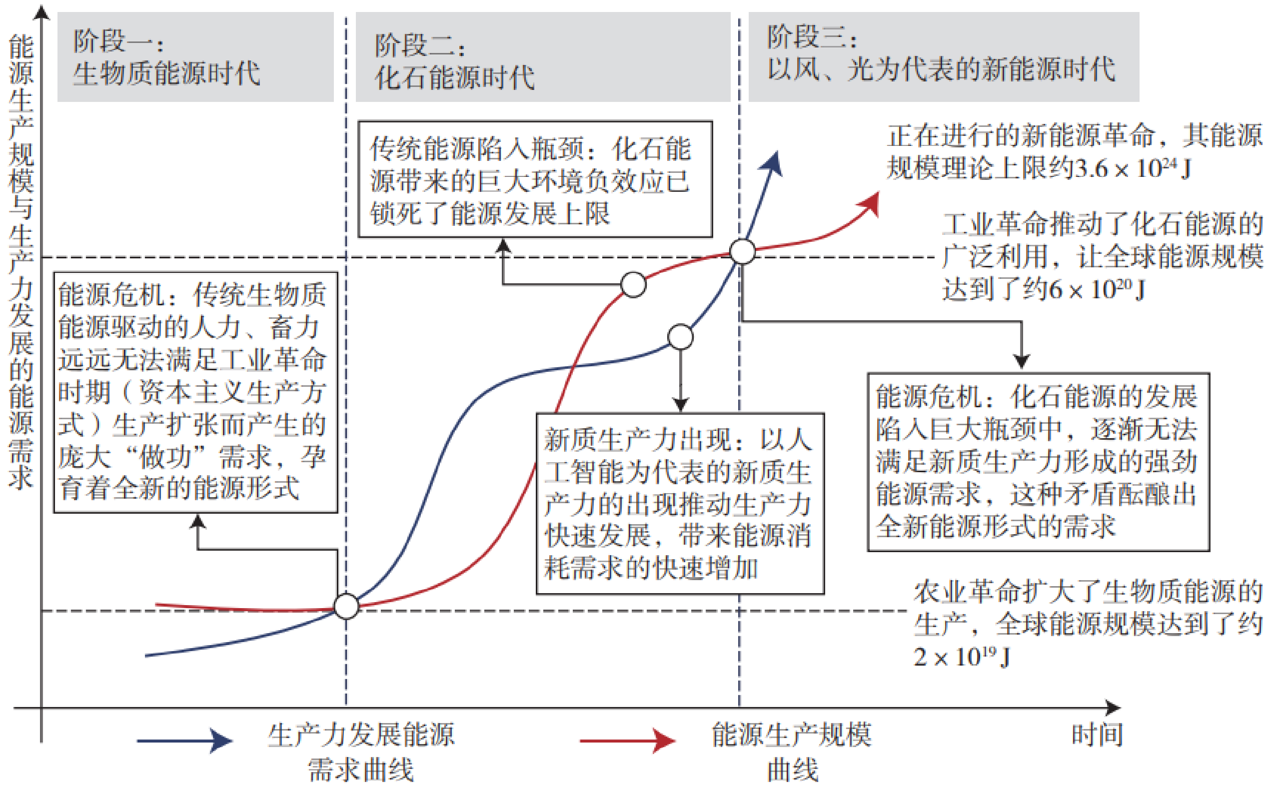

Figure 1. Schematic representation of the dialectical relationship between the development of “productive forces” and “energy”

2 “Renewable Energy” and “New” Forms of Land-Surface Use

2.1 Energy and land-surface use: energy transition is also a transition in land-surface use

Over the long history of human civilization, diverse energy forms have emerged—including biomass (food and firewood), fossil fuels (coal, petroleum, and natural gas), and contemporary renewable energy (photovoltaic, solar-thermal, and wind power). Each has generated a fundamentally different logic of land-surface use (Table 1). In agrarian societies dominated by biomass, its low spatial power density⑤ meant that energy production depended on securing more—and more productive—farmland so that plants could capture greater quantities of solar energy through photosynthesis. That energy, in turn, supported additional human and animal labor to meet the productive and subsistence needs of both states and individuals [29]. Land-surface resources were therefore central to energy production and became the most important measure of political power and wealth [30].

Table 1. Spatial characteristics associated with three major energy systems and their modes of energy production [31]

Characteristic	Biomass energy	Fossil energy	Renewable energy
Principal historical period	Before approximately 1800 CE	Approximately 1800 CE to the present	From the present onward
System category	Land-surface energy system	Subsurface energy system	Land-surface energy system
Main energy forms	Food and firewood	Coal, petroleum, natural gas, etc.	Wind and solar energy
Mechanism of energy formation	Surface vegetation captures solar energy through photosynthesis	Ancient biomass deposits are transformed through geological and geochemical processes over tens of millions of years	Wind and solar facilities directly or indirectly capture solar-derived energy at the Earth's surface
Principal motive power	Human and animal muscle	Steam engines, internal-combustion engines, etc.	Electric motors and information processing
Spatial power density of principal energy carriers (W/m^2)	0.03–0.18	135–500	1–8
Consumption of spatial resources in energy production	Very high	Low	Relatively high
Illustrative relative land requirement for producing an equivalent amount of energy	40 × 40 grid	1 × 1 grid	8 × 8 grid
Logic of expanding energy production	Expand the area of land-surface use to produce as much energy as possible	Invest in technology to extract subsurface energy more efficiently	Expand the area of land-surface use to capture and produce as much energy as possible
Pressure of energy production on land-surface use	High	Low	Relatively high
Spatial implications	Large areas are tied to energy production, strongly constraining land available for other functions	Only limited surface space is used for production and transport, leaving substantial land available for other human activities	Large areas are used for energy production, creating substantial pressure on space required for other activities

Note: The illustrative land requirements are calculated using representative spatial power densities of 0.08 W/m^2 for biomass, 135 W/m^2 for fossil energy, and 6 W/m^2 for renewable energy.

With the advent of industrial society, energy production shifted toward the exploration of larger and higher-quality subsurface mineral deposits and the construction of reliable trade routes capable of transporting energy efficiently to consumption centers around the world—primarily cities [32]. Because fossil fuels have high spatial power densities, energy production moved from the surface underground. Vast areas of land were no longer rigidly tied to energy production, providing the spatial basis for the rise of large cities and continuous urban regions [33]. Without the fundamental change in land-surface use brought about by the fossil-energy transition, the landscapes now taken for granted in modern society could not have emerged.

Modern cities and rural areas can therefore be understood as products of the fossil-energy transition that began more than two centuries ago [34]. The rise of wind and solar power is now transforming land-surface space once again into a primary carrier of energy production and is beginning to consume spatial resources on a large scale (Figure 2). Energy transition concerns not only technological forms but also “the social structures through which energy is acquired and managed,” of which space is a crucial component [35]. An energy transition is never merely technological; it is a broad and profound transformation of human society and, critically, of the ways in which space is used [36].

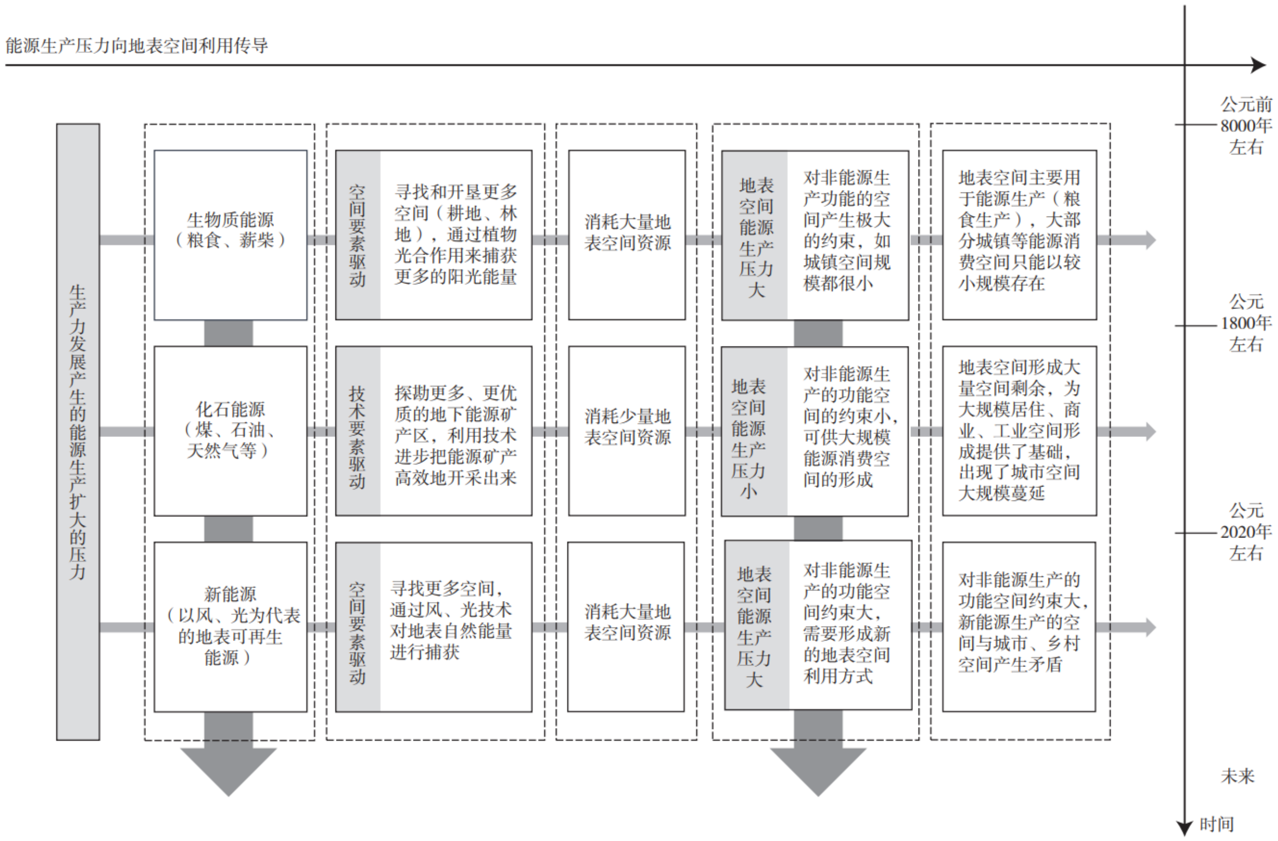

Figure 2. Relationship between energy transition and the transformation of land-surface use

2.2 New spatial demands of renewable energy: an energy-production system requiring extensive land-surface resources

The widespread adoption of wind and solar power marks a gradual departure from fossil energy extracted underground and a turn toward the direct use of natural energy generated by solar radiation at the Earth’s surface. Unlike the extremely uneven global distribution of fossil fuels, wind and solar resources are broadly distributed, widely accessible, and nearly universal. The “energy power” historically created by uneven fossil-resource distribution will therefore be weakened as renewable energy expands, potentially enabling a more equitable global energy geography [37]. In theory, renewable-energy development could produce a decentralized and distributed global supply system in which energy producers can no longer monopolize control over supply [38].

At the same time, wind and solar power have relatively low spatial power densities, generally only 1–6 W/m^2—two to three orders of magnitude lower than those of conventional fossil energy. Producing the same amount of energy therefore requires far more land-surface space. Vaclav Smil [39] has shown that a renewable-energy transition would consume enormous portions of a country's territory. The resulting landscapes will not resemble the picturesque image of small windmills and photovoltaic panels beside streams. Rather, renewable transition constitutes a pervasive form of spatial-industrial engineering unfolding throughout the principal spaces of human activity worldwide. Large-scale transition will require immense land areas, construction materials, labor, and capital, as well as the reconfiguration of socio-spatial relations [40]. Expansive energy landscapes will appear offshore and across fields, cities, Gobi regions, deserts, and hills (Figure 3). This is already a widespread phenomenon across China, Europe, the United States, and many other territories.

Compared with fossil fuels, renewable energy is clearly land-intensive. In theoretical terms, this shift gives much of the Earth's surface—formerly treated primarily as space for energy consumption—the potential to become space for energy production [41].

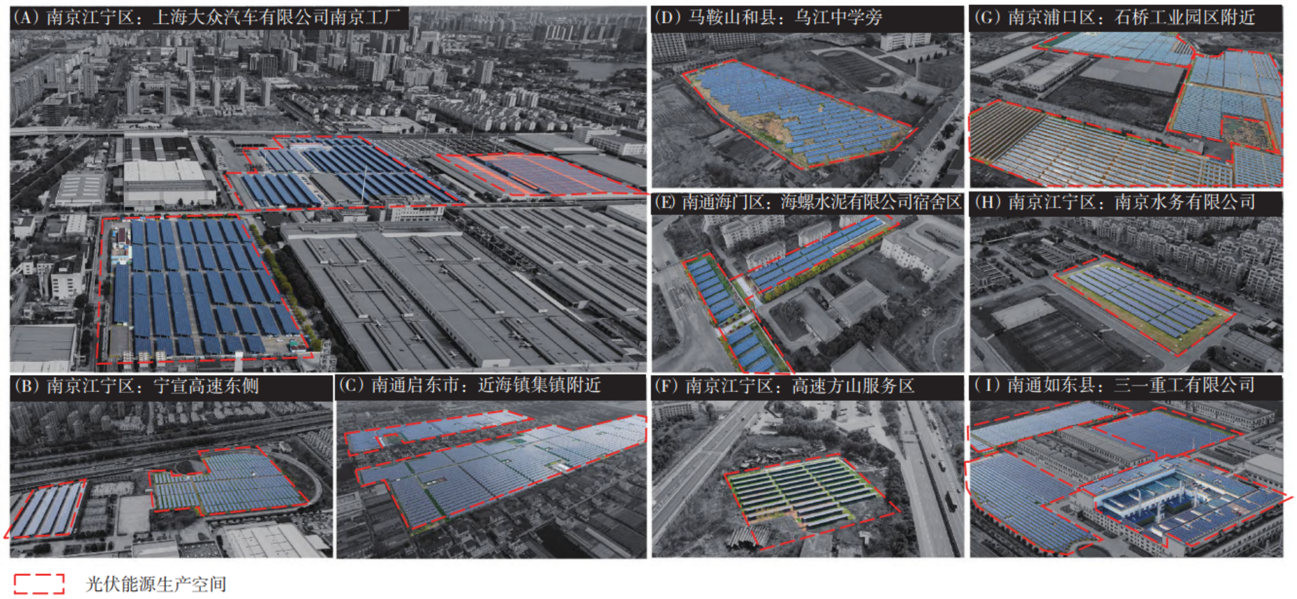

Figure 3. Typical photovoltaic energy-production cases that "consume substantial spatial resources"

2.3 A new dimension of land-surface development: "spatial energy production" challenges established patterns of spatial-resource use

Current land-surface use is a complex practical system organized around agriculture, residence, industry, commerce, transport, and ecology and carries multiple dimensions of economic, social, and aesthetic value. This system is powered by energy minerals formed underground through geological and geochemical processes over tens of millions of years. As Gavin Bridge [42] observes, energy materials are extracted from underground "holes" and brought to the surface as flows; mines, oil pumps, and gas valves serve as gateways between two worlds governed by fundamentally different spatial and temporal processes. Underground lies a world of "natural production" beyond direct human control, while the surface is a world produced by society. Once fossil energy is extracted, land-surface space primarily performs a transport function for "energy flows." These infrastructures are generally linear, spatially limited, and flexible in alignment, and remain instrumental to the economic, social, and ecological values of the surface [43]. Within a fossil-energy system, continuous and stable urban and rural energy supply can usually be maintained as long as these linear corridors remain secure and reliable.

The rapid diffusion of renewable-energy production introduces an entirely new dimension of land-surface development: spatial energy production. Space is no longer merely the background to energy activity but becomes a core element that directly participates in production; extensive areas of the Earth's surface acquire the potential to produce energy. Since the Industrial Revolution, spatial planning disciplines—including urban-rural planning and land-use planning—have sought to coordinate economic, social, ecological, and other values in the development of land-surface space, particularly in cities and rural areas, for the broader welfare of society. Renewable-energy production enables spaces previously considered difficult to exploit as resources to become energy-production sites, thereby challenging existing modes of spatial-resource use. The addition of “energy production” as a new variable in land-use systems will create new spatial conflicts and new demands for coordinated development.

Photovoltaic production provides a clear example. In practical terms, it resembles agriculture: both depend on exposure to sunlight. Its most direct requirement is the capture and occupation of solar radiation across a defined spatial area. Yet sunlight is a fundamental natural element in human living and production environments, supporting illumination, daylighting, sterilization and health, photosynthesis, and other spatial practices. Under the law of conservation of energy, when the sunlight received by a surface is converted into commercial energy, its other functions within that same space will necessarily be weakened or eliminated, potentially impairing the original use of the site.

Although the renewable-energy transition remains at an early stage, conflicts between land-surface energy production and existing land-use systems are already widespread. They include the occupation of farmland by renewable-energy facilities [44], spatial injustice produced by “green grabbing” [45], conflicts between energy infrastructure and cultural landscapes [46], and tensions between renewable-energy installations and the intensive use of industrial land (Figure 4). These early manifestations indicate that the emergence of spatial energy production is already disrupting conventional concepts and institutions of land-surface use.

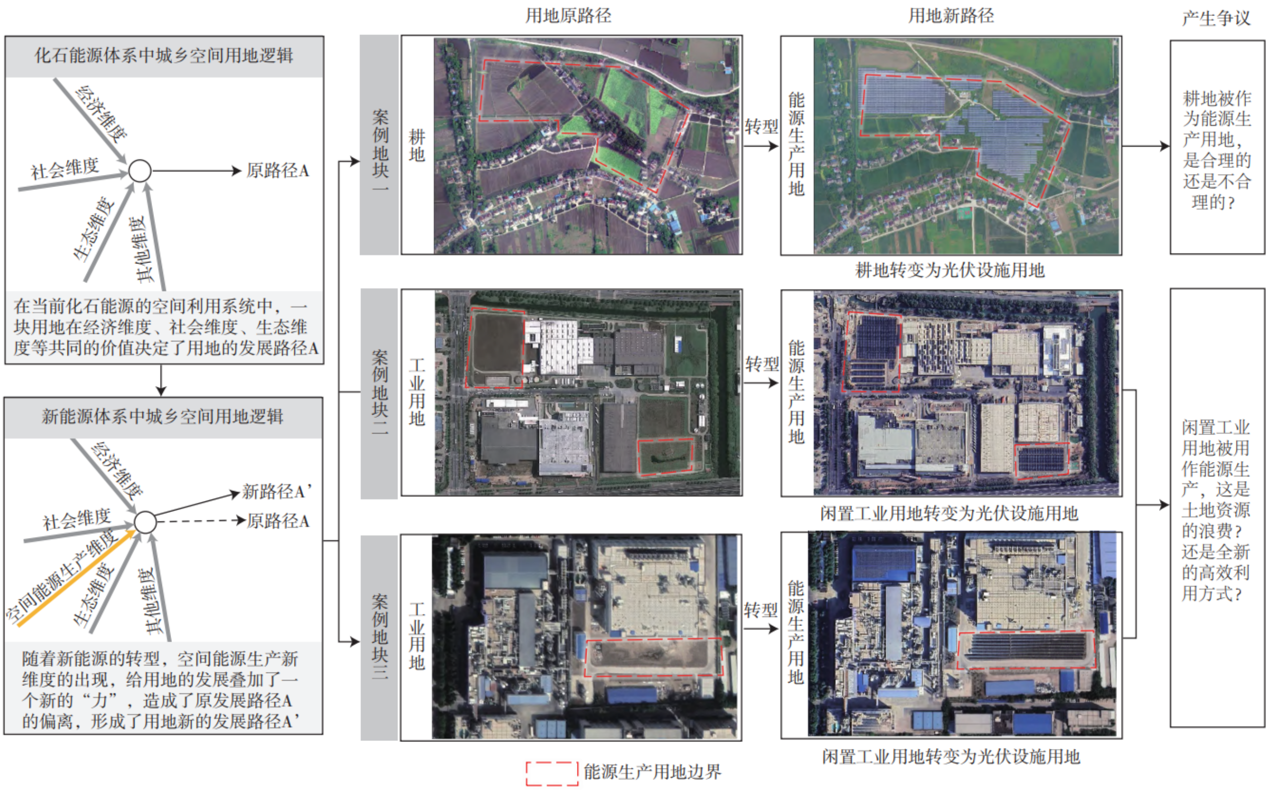

Figure 4. Schematic representation and illustrative cases of altered land-use pathways under “spatial energy production”

Note: (1) Energy-production land within the industrial sites shown here refers to ground-mounted photovoltaic facilities rather than the less controversial rooftop photovoltaic systems. (2) Case 1 is located in Yangzhong; Case 2 in Suzhou Industrial Park; and Case 3 in Nantong Economic and Technological Development Area.

3 The Role, Limitations, and Evolution of Territorial Spatial Planning within the "Productive Forces–Energy–Space" Framework

3.1 Formation of the "productive forces–energy–space" framework

With the rapid development of renewable energy, "productive forces" and "space" are becoming increasingly interconnected through energy. The preceding discussion reveals a concise logic within the development of new quality productive forces. First, their growth requires greater energy support, stimulating the emergence of more diverse energy sources and higher conversion efficiencies and thereby accelerating renewable-energy production in practice. Second, renewable energy depends on capturing energy distributed across the Earth's surface. Its rapid expansion therefore requires both a greater supply of spatial resources and more efficient use of space, directly challenging existing patterns of land-surface use. Under this logic, spatial-resource supply and utilization become key foundations for the development of new quality productive forces. This relationship can be summarized in the principle "space is energy, and energy is productive capacity," which forms the basis of the "productive forces–energy–space" analytical framework (Figure 5).

Within this framework, space is the foundation of energy, and energy is the foundation of productive capacity. The relationship among the three, however, is not simply linear. This paper does not endorse either "energy determinism" or its possible extension into "spatial determinism." From the perspective of historical materialism, the widespread use of fossil fuels did not directly determine the specific technical forms of the steam engine or internal-combustion engine. Likewise, large-scale renewable-energy production will not directly determine the precise forms taken by artificial intelligence, robotics, or brain-computer interfaces. Nevertheless, abundant energy supply resembles the fertile soil of a tropical rainforest: it provides the foundation from which many "towering trees" can emerge and grow.

Historical experience shows that the development of any new quality productive force is contingent and uncertain. Effective planning and management of land-surface resources, however, can build a reliable and continuously expanding energy-supply base and thereby create a stable social foundation for the development of new quality productive forces. If China were able to increase its energy-production capacity by one order of magnitude, it would provide fertile ground for the emergence of diverse new productive forces and constitute a major strategic advantage in international competition. The creation of this foundation depends on how society understands and uses land-surface space, which gives territorial spatial planning a crucial role in the framework.

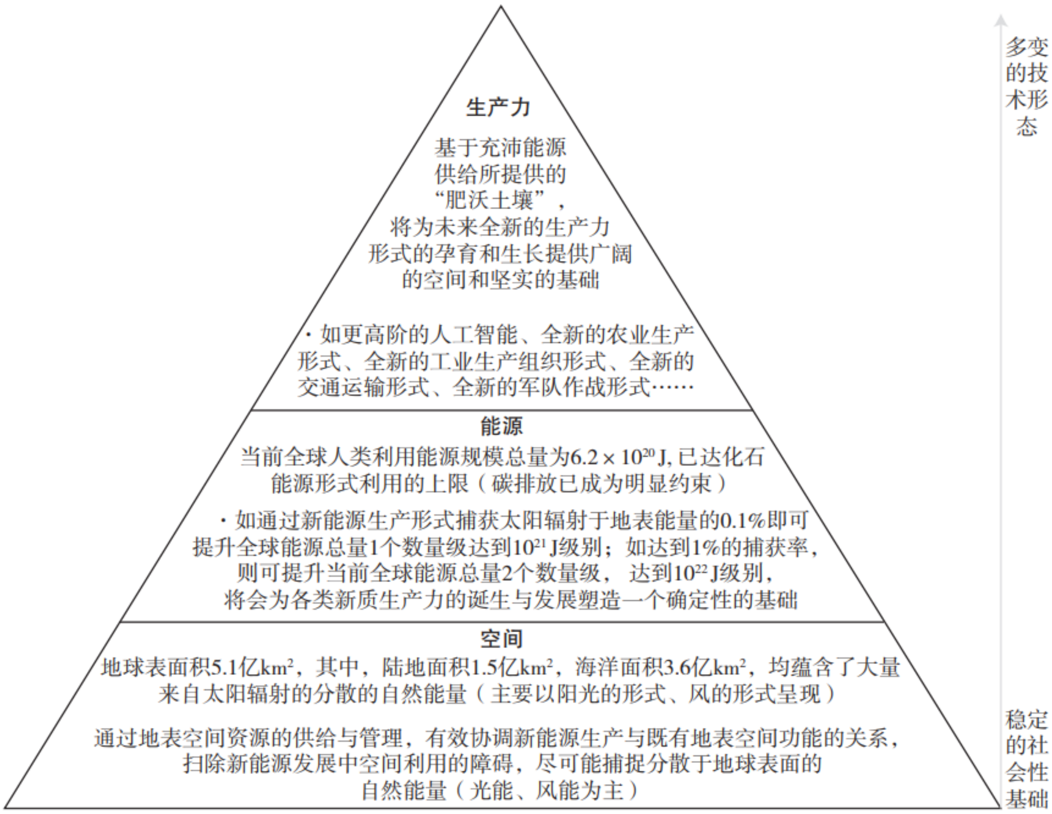

Figure 5. Schematic representation of the "productive forces–energy–space" framework based on renewable energy

3.2 Territorial spatial planning within the "productive forces–energy–space" framework

3.2.1 Planning function: managing vast "spatial-energy" assets through territorial governance

China has initially established a territorial spatial planning system that extends vertically through all administrative levels and horizontally across the full range of spatial categories. In principle, this provides a practical framework for planning, coordinating, and governing the entire national territory [47-48]. Under the principle that "space is energy, and energy is productive capacity," territorial spatial planning bears responsibility for managing the natural energy resources embedded across China's 9.6 million km^2 of land surface and therefore has an important influence on the energy foundation of new quality productive forces.

A preliminary estimate indicates that the solar-radiation resource contained within China's territorial surface amounts to approximately 5.2×10^{22} J annually⑥—more than 300 times China's total energy consumption in 2022, which was approximately 1.6×10^{20} J. The emergence of renewable energy thus adds an energy-production dimension to the mountains, rivers, forests, farmland, lakes, grasslands, seas, and cities governed through territorial spatial planning.

In most other functional spaces managed by territorial spatial planning—residential, industrial, and commercial areas, for example—space serves as the carrier rather than the substance of the relevant activity, and planning intervention is therefore largely indirect. In renewable-energy production, by contrast, energy comes from the extensive land surface itself; space is an intrinsic component of the productive activity. Planning intervention is consequently more direct and can significantly affect the pace and form of China's renewable-energy transition and, by extension, the foundation on which new quality productive forces develop.

3.2.2 Current limitation: spatial tools formed in the fossil-energy era do not match renewable-energy requirements

The establishment of territorial spatial planning creates the possibility of managing renewable-energy resources at the national scale. In practice, some regions have already used territorial spatial planning to coordinate conflicts between renewable-energy production and conventional functional space. China's natural-resource authorities, for example, have issued several rounds of land-management guidance in response to the occupation of farmland by renewable-energy facilities [49]. At a deeper level, however, these conflicts arise because the "old" instruments and concepts of current territorial spatial planning cannot effectively understand or govern new phenomena.

To avoid conflict with established surface functions, renewable-energy development has so far concentrated on rooftop photovoltaics, photovoltaic facilities in deserts and Gobi regions, and nearshore or offshore wind power—using spaces traditionally regarded as having little productive value. These forms have generated substantial benefits, but the range of resource use remains limited and still falls far short of comprehensive development of energy embedded across the full land surface.

At the level of fundamental spatial concepts, the current cognitive framework of territorial spatial planning remains rooted in the static spatial paradigm of classical physics, which simplifies space as a three-dimensional linear container defined by length, width, and height. Instruments such as use regulation and project lists essentially operate as "permit–prohibit" mechanisms governing the occupation of three-dimensional space⑦. Renewable-energy production, however, treats space itself as an intrinsic part of the productive process. Solar-energy capture depends on two-dimensional planar surfaces defined by length and width [50], whereas wind-energy capture depends on the fluid space created by moving air.

Given these differences, planning instruments inherited from the fossil-energy paradigm can neither establish appropriate performance evaluations for renewable-energy land use nor effectively guide the allocation of spatial factors. If traditional spatial concepts remain unchanged, even immense energy assets will be difficult to use effectively or convert into material productive capacity.

3.2.3 Evolutionary direction: upgrading and creating spatial tools for renewable-energy development

Planning must return to the fundamental relationship between energy production and space and recognize, at the epistemological level, the different spatial concepts associated with renewable and fossil energy. Focusing on the capture of sunlight and moving air, it is necessary to develop new cognitive, analytical, and practical methods capable of coordinating renewable-energy production with other land-surface functions.

First, planning should establish a comprehensive conception of energy. The normal functioning of contemporary cities depends not only on fossil-energy supply but also on the direct contribution of abundant natural energy to daylighting, heating, sterilization and health, ventilation, and photosynthesis. According to the law of conservation of energy, converting natural energy into commercial energy inevitably weakens or removes its original functions. This is particularly important for sunlight: planners must determine which solar-energy functions are "essential" to urban operations, which are "nonessential," and which represent "waste," in order to identify which natural energy flows may appropriately be converted into energy production.

Second, spatial planning should establish analytical methods linking space and energy. For solar energy, this requires mapping light projection onto land-surface space and constructing evaluation models for the scale and efficiency of solar-energy use. For wind energy, analysis should focus on the spatial externalities of wind-energy development, including noise, disturbance to animal communities, and resistance arising from cultural-landscape impacts.

Third, planning should strengthen the governance of three-dimensional space and upgrade its toolkit. Conventional instruments—including floor-area ratio, green-space ratio, height limits, and building density—should be improved. At the same time, new concepts and instruments should be created specifically for renewable-energy systems in order to increase the efficiency of spatial energy production and reduce conflicts with other land-surface functions.

Fourth, an innovative property-rights system for energy space is required. Photovoltaic production captures energy through a series of two-dimensional surface areas. Existing property-rights arrangements should therefore be extended beyond conventional land and building ownership to establish spatial rights specifically designed for energy production.

4 Conclusions and Discussion

New quality productive forces are a strategic means by which China can seize the initiative in global competition, achieve leapfrog improvements in national productivity, and promote high-quality development. Spatial planning should respond to the direction of the times by actively supporting wind- and solar-energy development, participating in the new energy revolution, and strengthening the energy foundation required by new quality productive forces.

This paper integrates productive forces, energy, and space within a unified analytical framework. First, it identifies renewable energy as a foundational condition for the development of new quality productive forces. Historically, qualitative shifts in productivity have usually been preceded or accompanied by innovation in energy forms; today, the supply ceiling of fossil energy has become a systemic constraint on further productivity growth. Second, energy revolution is fundamentally a revolution in land-surface use. Wind and solar development overturns the spatial logic of conventional energy systems and gives much of the Earth's surface—previously understood primarily as space of energy consumption—the potential to become space of energy production. This creates a new form of land use, "spatial energy production," which generates new value while challenging established systems of spatial use. Energy transition is therefore not merely a change in energy technology but a broad and profound transformation of human society and of the fundamental ways in which space is used.

Finally, the paper develops a "productive forces–energy–space" framework and argues that effective planning and management of land-surface resources should create a reliable and expanding energy-supply foundation for new quality productive forces. Territorial spatial planning should bear significant responsibility for managing the immense spatial-energy resources embedded across the entire national territory. Yet planning concepts and instruments formed within the fossil-energy system cannot adequately evaluate or guide the development of renewable-energy forms. Territorial spatial planning must therefore return to the fundamental relationship between energy production and space and upgrade both its conceptual foundations and practical instruments by: (1) establishing a comprehensive conception of energy; (2) developing analytical methods linking space and energy; (3) strengthening three-dimensional spatial governance and upgrading planning instruments; and (4) innovating systems of spatial property rights for energy production.

Planetary-scale renewable-energy use once belonged largely to science fiction. Rapid technological development and broad social participation are now making it a practical reality, and the futurist transformation of land-surface use associated with renewable energy is already unfolding. Historical experience, however, shows that energy and spatial transitions are never completed overnight; they are large historical processes that may extend over decades or even a century [51]. China should therefore use the "productive forces–energy–space" framework as soon as possible to pursue an order-of-magnitude increase in energy-production capacity, create new spatial concepts and planning tools, guide the transformation of territorial spatial planning, and advance spatial practice oriented toward renewable-energy development.

Notes

① The Kardashev index is calculated as $K = (\log_{10}P - 6) / 10$, where K is a civilization's Kardashev index and P is the amount of power it uses. On this basis, civilizations are divided into Types I, II, and III. A Type I civilization can harness all renewable energy available on its planet, including solar, wind, and hydropower; a Type II civilization can harness energy on the scale of a star; and a Type III civilization can harness energy on the scale of a galaxy. Humanity is currently estimated to be a Type 0.73 civilization.

② This comparison considers only the total amount of work performed and does not account for energy quality. If energy quality were included, the difference between the life of an ordinary modern person and that of an ancient aristocrat would be even greater.

③ In the nineteenth century, coal was a new energy source relative to traditional biomass such as food and firewood; in the twentieth century, petroleum was a new energy source relative to coal.

④ TWh denotes terawatt-hours and is equivalent to 10^9 kWh.

⑤ Spatial power density refers to the amount of energy produced per unit of land-surface area in energy-production practice, measured in W/m^2. A higher spatial power density generally means that less spatial resource is required to produce a given amount of energy, whereas a lower density requires more space.

⑥ The solar-radiation energy contained within China's territory is estimated using $E = S \times H$, where E is total annual solar-radiation energy, S is China's territorial area (9.6 million km^2), and H is the average annual global horizontal irradiation across China (1,493.4 kWh/m^2). This simplified estimate is not precise, but it indicates the order of magnitude of spatial energy embedded in the national territory.

⑦ Although use regulation may appear to govern a two-dimensional land surface, in practice it also incorporates height-related indicators such as floor-area ratio and height limits and therefore constitutes a form of three-dimensional spatial governance.

References

[1] WU Zhiqiang, YAN Juan, XU Haowen, et al. Ten key annual issues in the development of urban and rural planning (2024–2025) [J]. Urban Planning Forum, 2024(6): 8–11. [in Chinese]

[2] SHEN Qingji. Sustainable urban energy development in China: an urban-planning perspective [J]. Urban Planning Forum, 2005(6): 41–47. [in Chinese]

[3] HUBER M. T. Theorizing energy geographies [J]. Geography Compass, 2015, 9(6): 327–338.

[4] BRIDGE G., BOUZAROVSKI S., BRADSHAW M., et al. Geographies of energy transition: space, place and the low-carbon economy [J]. Energy Policy, 2013, 53: 331–340.

[5] YANG Yu, XIA Siyou, JIN Zhijun. The logic and research prospects of geopolitical restructuring driven by energy transition [J]. Acta Geographica Sinica, 2023, 78(9): 2299–2315. [in Chinese]

[6] MORONI S., ANTONIUCCI V., BISELLO A. Energy sprawl, land taking and distributed generation: towards a multi-layered density [J]. Energy Policy, 2016, 98: 266–273.

[7] ZHU D., SONG D., SHI J., et al. The effect of morphology on solar potential of high-density residential area: a case study of Shanghai [J]. Energies, 2020, 13(9): 2215.

[8] HU M., SONG X., BAO Z., et al. Evaluation of the economic potential of photovoltaic power generation in road spaces [J]. Energies, 2022, 15(17): 6408.

[9] ZHANG Bing, ZHU Yingying, LAN Chun, et al. Nature-based solutions: cognition and conservation planning methods for historic urban environments under climate change [J]. Urban Planning Forum, 2024(1): 18–28. [in Chinese]

[10] SUN Shiwen. Basic research on the implementation and supervision system of territorial spatial planning [J]. Urban Planning Forum, 2024(2): 12–17. [in Chinese]

[11] ZHANG Shangwu. The technical system of territorial spatial planning: top-level architecture and key breakthroughs [J]. Urban Planning Forum, 2022(5): 45–50. [in Chinese]

[12] WU Zhiqiang, GUO Renzhong, ZHANG Bing, et al. Academic discussion on the systematic construction of the national spatial planning system [J]. Urban Planning Forum, 2024(5): 1–11. [in Chinese]

[13] WANG Kai, ZHAO Yanjing, ZHANG Jingxiang, et al. Academic discussion on new quality productive forces and urban-rural planning [J]. Urban Planning Forum, 2024(4): 1–10. [in Chinese]

[14] BRIDGE G. Material worlds: natural resources, resource geography and the material economy [J]. Geography Compass, 2009, 3(3): 1217–1244.

[15] KARDASHEV N. S. Transmission of information by extraterrestrial civilizations [J]. Soviet Astronomy, 1964, 8: 217.

[16] SMIL V. Energy Transitions: Data, History, and Prospects [M]. Trans. GAO Feng, JIANG Aixin, LI Hongda. Beijing: Science Press, 2018. [Chinese edition]

[17] SMIL V. World history and energy [J]. Encyclopedia of Energy, 2004, 6: 558.

[18] XINHUA NEWS AGENCY. Xi Jinping stresses accelerating the development of new quality productive forces and steadily advancing high-quality development at the eleventh group study session of the Political Bureau of the CPC Central Committee [EB/OL]. (2024-02-10) [2024-09-28]. https://www.gov.cn/yaowen/liebiao/202402/content_6929446.htm. [in Chinese]

[19] CUI Shoujun, CAI Yu, JIANG Moqian. Major technological change and the transformation of energy geopolitics [J]. Journal of Natural Resources, 2020, 35(11): 2585–2595. [in Chinese]

[20] RITCHIE H., ROSADO P., ROSER M. Energy Production and Consumption [EB/OL]. (2024-01) [2024-09-28]. https://ourworldindata.org/energy-production-consumption.

[21] BRIDGE G., LE BILLON P. Oil [M]. Cambridge: Polity Press, 2012.

[22] MCNEILL J. R. Something New under the Sun: An Environmental History of the Twentieth Century [M]. New York: W. W. Norton, 2000.

[23] MARX K., ENGELS F. The Communist Manifesto [EB/OL]. (2019-11-21) [2024-09-28]. https://www.thepaper.cn/newsDetail_forward_5037841. [Chinese online edition]

[24] HUBER M. T. Energizing historical materialism: fossil fuels, space and the capitalist mode of production [J]. Geoforum, 2009, 40(1): 105–115.

[25] CALVERT B. AI already uses as much energy as a small country. It's only the beginning [EB/OL]. (2024-03-28) [2024-09-28]. https://www.vox.com/climate/2024/3/28/24111721/climate-ai-tech-energy-demand-rising.

[26] SHI Dan, SHI Kehan. The role of renewable energy in developing new quality productive forces [EB/OL]. (2024-06-05) [2024-09-28]. https://mp.weixin.qq.com/s?__biz=MzI0NDAzMjA5Nw==&mid=2654909767&idx=1&sn=2177cb9ee8738ed358207bb36146eb28&chksm=f2a9e249c5de6b5f7a416492e3cc7c7785e055d580f1e675a3546fd6d92a73031c8eeb06835b&scene=27. [in Chinese]

[27] BLAIN L. Elon Musk: AI will run out of electricity and transformers in 2025 [EB/OL]. (2024-03-01) [2024-09-28]. https://newatlas.com/technology/elon-musk-ai/.

[28] DE VRIES B. J. M., VAN VUUREN D. P., HOOGWIJK M. M. Renewable energy sources: their global potential for the first half of the 21st century at a global level—an integrated approach [J]. Energy Policy, 2007, 35(4): 2590–2610.

[29] WRIGLEY E. A. Continuity, Chance and Change: The Character of the Industrial Revolution in England [M]. Cambridge: Cambridge University Press, 1990.

[30] SIEFERLE R. P. The Subterranean Forest: Energy Systems and the Industrial Revolution [M]. Cambridge, UK: White Horse Press, 2001.

[31] VAN ZALK J., BEHRENS P. The spatial extent of renewable and non-renewable power generation: a review and meta-analysis of power densities and their application in the US [J]. Energy Policy, 2018, 123: 83–91.

[32] YANG Yu, XIA Siyou, QIAN Xiaoying. Geopolitical research on energy transition [J]. Acta Geographica Sinica, 2022, 77(8): 2050–2066. [in Chinese]

[33] NIKIFORUK A. The Energy of Slaves: Oil and the New Servitude [M]. Vancouver: Greystone Books, 2014.
[34] RUTHERFORD J., COUTARD O. Urban energy transitions: places, processes and politics of socio-technical change [J]. Urban Studies, 2014, 51(7): 1353–1377.
[35] PASQUALETTI M. J., BROWN M. A. Ancient discipline, modern concern: geographers in the field of energy and society [J]. Energy Research & Social Science, 2014, 1: 122–133.
[36] COENEN L., TRUFFER B. Places and spaces of sustainability transitions: geographical contributions to an emerging research and policy field [J]. European Planning Studies, 2012, 20(3): 367–374.
[37] YANG Yu, HE Ze. Energy geopolitics and energy power [J]. Progress in Geography, 2021, 40(3): 524–540. [in Chinese]
[38] WEINRUB A. Expressions of Energy Democracy: Perspectives on an Emerging Movement [R/OL]. (2014-08) [2025-03-04]. https://www.localcleanenergy.org/files/Expressions%20of%20Energy%20Democracy.pdf.
[39] SMIL V. Power Density: A Key to Understanding Energy Sources and Uses [M]. Boston: MIT Press, 2015.
[40] HUBER M. T., MCCARTHY J. Beyond the subterranean energy regime? Fuel, land use and the production of space [J]. Transactions of the Institute of British Geographers, 2017, 42(4): 655–668.
[41] CALVERT K. From ‘energy geography’ to ‘energy geographies’: perspectives on a fertile academic borderland [J]. Progress in Human Geography, 2016, 40(1): 105–125.
[42] BRIDGE G. The Hole World: Scales and Spaces of Extraction [EB/OL]. (2015-09-01) [2024-09-28]. https://scenariojournal.com/article/the-hole-world/.
[43] CALVERT K., SIMANDAN D. Energy, space, and society: a reassessment of the changing landscape of energy production, distribution, and use [J]. Journal of Economics and Business Research, 2010, 16(1): 13–37.
[44] XIA Z., LI Y., GUO S., et al. Balancing photovoltaic development and cropland protection: assessing agrivoltaic potential in China [J]. Sustainable Production and Consumption, 2024, 50: 205–215.
[45] HOLMES G. What is a land grab? Exploring green grabs, conservation, and private protected areas in southern Chile [J]. Journal of Peasant Studies, 2014, 41(4): 547–567.
[46] COWELL R. Wind power, landscape and strategic spatial planning: the construction of ‘acceptable locations’ in Wales [J]. Land Use Policy, 2010, 27(2): 222–232.
[47] YANG Baojun, CHEN Peng, DONG Ke, et al. Constructing a territorial spatial planning system in the context of ecological civilization [J]. Urban Planning Forum, 2019(4): 16–23. [in Chinese]
[48] ZHAO Min. The logic and operational strategies of constructing a territorial spatial planning system [J]. Urban Planning Forum, 2019(4): 8–15. [in Chinese]
[49] GENERAL OFFICE OF THE MINISTRY OF NATURAL RESOURCES, GENERAL OFFICE OF THE NATIONAL FORESTRY AND GRASSLAND ADMINISTRATION, GENERAL DEPARTMENT OF THE NATIONAL ENERGY ADMINISTRATION. Notice on supporting the development of the photovoltaic power industry and standardizing land-use management [R/OL]. (2023-03-20) [2024-09-28]. https://www.gov.cn/zhengce/zhengceku/2023-04/03/content_5749824.htm. [in Chinese]
[50] WANG Yizhe. Spatial energy production: a new pathway for low-carbon transformation of urban space in the renewable-energy era—from the perspective of interactive integration between photovoltaic production and urban space [J]. City Planning Review, 2024, 48(4): 59–70. [in Chinese]
[51] GRUBLER A. Energy transitions research: insights and cautionary tales [J]. Energy Policy, 2012, 50: 8–16.
Revised manuscript received: February 2025.

AI-assisted translation