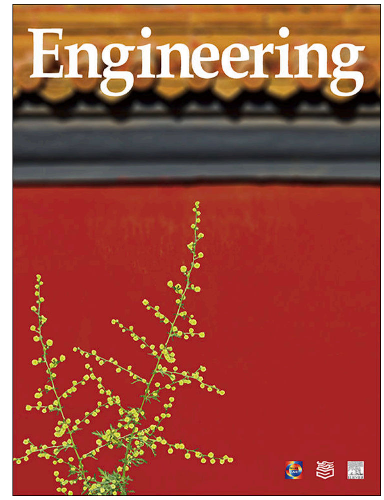

Article

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Views & Comments

Global Energy Transition Through the Lens of Metacoupling

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1. Introduction

The global energy transition refers to the process of transitioning from traditional energy sources, such as fossil fuels, to renewable energy sources [1]. It is crucial for mitigating climate change, enhancing energy security, and promoting sustainable development. However, the global energy transition faces several challenges. Emerging technologies, such as artificial intelligence and energy storage, may have difficulties in terms of scalability and accessibility. Additionally, geopolitical tensions may undermine regional energy security and hinder energy trade.

Moreover, the process of global energy transition is heavily influenced by social justice concerns [2]. A core challenge is ensuring a "just energy transition," which entails a fair distribution of its associated costs and benefits [3]. This is particularly acute in developing nations, where approximately 1 billion people lack reliable access to electricity, and many depend on traditional biomass for cooking [4].

In the energy transition, technology, trade, policy, and other factors are linked together. While funding for energy innovation can accelerate technological advancement and the energy transition, suboptimal energy policies can undermine these gains [5]. The development of energy technologies promoted international energy trade. At the same time, the demand for trade has accelerated the application of emerging technologies, facilitating the process of global energy transition [6]. Governments and policymakers can support energy transition through policies such as setting renewable energy targets, supporting energy technology development, and providing subsidies [7].

To address problems in the energy transition, comprehensive analytical tools are necessary. The metacoupling framework emerges as a relevant tool in this context. By focusing on human–nature interactions within as well as between adjacent and distant systems, it provides a comprehensive perspective to analyze these interactions during the energy transition [8]. The metacoupling framework allows researchers and policymakers to move beyond isolated perspectives on the energy transition and adopt a more integrated approach to address economic and social issues as well as environmental issues across multiple systems and scales, from local to global.

This paper first provides an overview of the metacoupling framework, as shown in Fig 1 [8], illustrates how each of its three dimensions works for the energy transition with examples, then discusses challenges of the energy transition, and finally offers policy recommendations to overcome those challenges. Through a systematic analysis of the interdependencies involved in the global energy transition under the metacoupling framework, this paper aims to offer insights into policies that align local needs with global sustainability goals, ultimately achieving a just and resilient global energy transition.

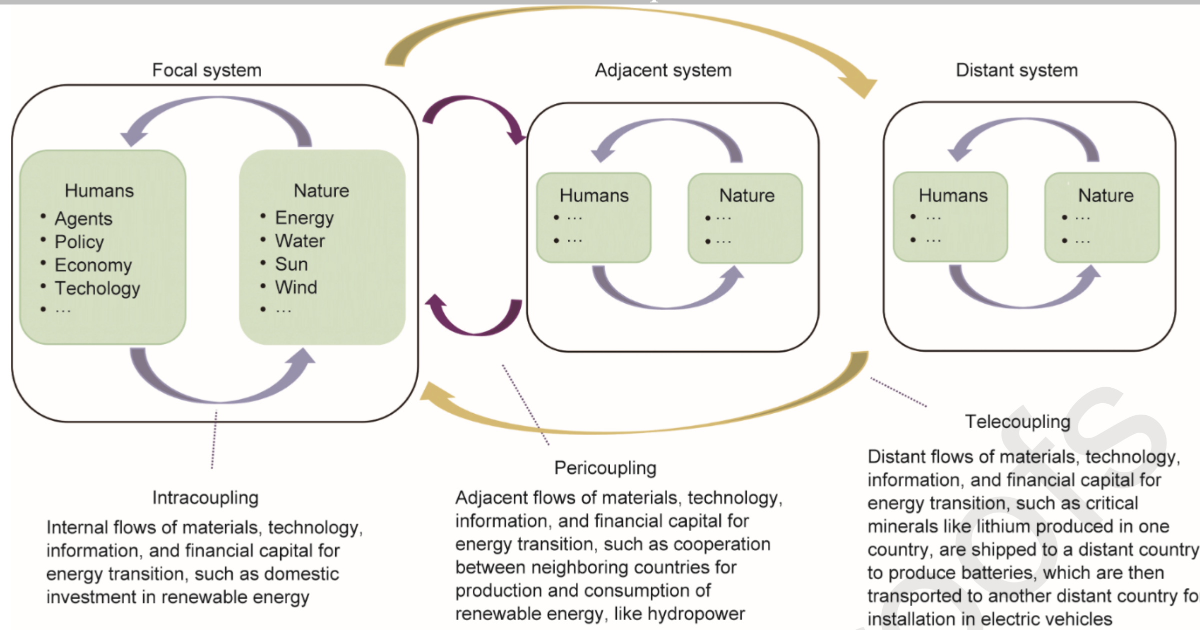

Fig. 1. A diagram of the metacoupling framework and application to global energy transition. Each box represents a coupled human–nature system, such as a country, which consists of humans (e.g., policy, economic) and nature (e.g., energy, water). Within a system, humans and nature are connected through flows, such as information dissemination, to shape the energy transition (intracoupling, blue line). Adjacent systems are connected through flows such as cross-border cooperation between neighboring systems (pericoupling, purple line). Furthermore, distant systems are also connected through global flows, such as distant supply chains, to influence the global energy transition (telecoupling, yellow line). The figure is modified from Ref. [8].

2. Overview of the metacoupling framework and its relevance to energy transition

Energy transition involves the issue of sustainable human development. In recent years, many articles have reported research on sustainable development [9–12]. The metacoupling framework provides a comprehensive approach to analyzing the human–nature interactions that shape the global energy transition. It encompasses three dimensions: intracoupling (human–nature interactions within a system such as a country), pericoupling (human–nature interactions between adjacent systems), and telecoupling (human–nature interactions between distant systems) [13] (Fig.1). The framework has been applied to a wide range of issues, such as nature's contributions to people [14], energy–food–water nexus [15], global trade networks [16], CO_2 emissions [17], and the United Nations Sustainable Development Goals [18].

This multi-scale perspective is essential because it outlines how local, regional, and global human–nature interactions converge to influence the global energy transition.

There are many agents, such as participants and stakeholders, in the energy transition. Considering a country as a system, the intracoupling-level stakeholders include policymakers who design transition pathways, fossil fuel-dependent industries, renewable energy developers, and consumers affected by changes in energy prices and infrastructure. At the pericoupling level, stakeholders are typically the governments and companies of neighboring countries, which collaborate on cross-border projects. At the telecoupling level, the main players are resource-rich countries, production-dominant countries, and energy-consuming countries. They are tightly linked by global supply chains, even though they are geographically distant.

Intracoupling refers to the human–nature interactions within a single system, such as a country. In the energy transition, this involves how a nation's human components (e.g., government policies and technological innovation) interact with its natural components (e.g., energy resources and climate conditions). For example, when a country invests in renewable energy or upgrades its electricity grid, it demonstrates intracoupling, in which national policies directly influence domestic energy production and consumption patterns.

Pericoupling refers to interactions between adjacent systems (e.g., neighboring countries), manifested in shared infrastructure and cross-border energy trade. For instance, Canada and the United States have built an interconnected power grid, and Canada exports a large amount of hydropower to the United States. This has improved the power stability of the United States and promoted the development of hydropower in Canada [19].

Telecoupling is the most expansive dimension, referring to the links between distant systems through global flows of energy, materials, finance, information, and technology. For example, mined in one country (e.g., Australia), critical minerals like lithium and cobalt are shipped to a distant country (e.g., China) for processing and manufacturing into battery cells [20]. Finally, these batteries are transported to another distant country, such as Germany [21]. This telecoupled chain has accelerated the energy transition by lowering technology costs [22].

The metacoupling framework encompasses intracoupling, pericoupling, and telecoupling. It effectively describes the multi-scale dynamics of the global energy transition. Take the expansion of oil and gas production in the United States as an example:

(1) Domestically, it generated substantial economic benefits, including job creation and energy security. However,

increased oil and gas production runs counter to energy transition goals and raises environmental concerns due to extraction activities.

(2) Regionally, the United States and Canada share a highly integrated energy system. The United States has transformed from an importer to an exporter, and the expansion of oil and gas production directly impacted the market for Canadian oil exports.

(3) Globally, the liquefied natural gas (LNG) from the United States offers European countries an alternative to Russian gas. At the same time, the increase in fossil fuel supply also influences global energy prices, potentially slowing the adoption of renewables in other countries.

By integrating these dimensions, the metacoupling framework enables researchers and policymakers to devise more effective and equitable ways to achieve the energy transition within and across systems near and far. Below, we will discuss each of these three dimensions in more detail.

3. Intracoupling: Domestic energy transitions and challenges

Intracoupling—the interaction of technologies, policies, and socioeconomic and environmental factors within a system—helps researchers and stakeholders understand what influences the energy transition in that system.

(1) **Renewable energy deployment.** Deployment of renewable energy sources, including solar, wind, and hydro, is crucial to the energy transition. However, integrating these energy sources into the existing energy system will pose challenges to the energy infrastructure. Since renewable energy sources are volatile, it is necessary to upgrade grid infrastructure, such as equipping more energy storage equipment, to ensure the reliability and stability of the system.

(2) **Fossil fuel phase-out policies and resistance**. Energy transition requires a significant reduction in the consumption of fossil fuels, including coal and oil. Therefore, it is crucial to develop effective policies to phase out fossil fuels. However, these policies are often resisted by the industries and regions that rely heavily on traditional energy.

(3) **Socioeconomic impacts**. The energy transition is likely to affect workers in traditional energy industries like coal mining and oil extraction. During the energy transition, as the fossil fuel industry declines, there could be massive job losses and economic disruption. Therefore, policymakers should prioritize a "just transition," including the implementation of targeted support and retraining programs for workers in traditional energy industries.

A classic example of intracoupling is Germany's Energiewende, a strategy to shift its energy system towards sustainable energy. One of its core goals is to achieve an 80% share of renewable energy in electricity consumption by 2050. The Energiewende has made significant progress; by 2020, renewable energy accounted for over 40% of Germany's electricity production [23].

Despite these advancements, the Energiewende still faces several challenges. First, insufficient transmission capacity has led to grid congestion, which prevents wind power from being transmitted from the north to industrial centers in the south. Second, high renewable energy subsidy costs have pushed German household electricity prices to among the highest in Europe, exceeding 0.30 $\mathrm{EUR\cdot(kW\cdot h)^{-1}}$, imposing an additional burden on low-income households. Furthermore, as fossil fuels are gradually phased out, regions that rely on coal face the risk of unemployment and economic stagnation [24]. This directly impacts tens of thousands of jobs in mining and power generation in regions like Lusatia and the Rhineland, making the energy transition more complicated.

Germany's experience shows that the progress of a country or region's energy transition is affected by many factors, including infrastructure development, the coordinated integration of diverse energy sources, and people's livelihoods. Therefore, it is crucial to implement effective policies to combine the expansion of renewable energy with the reduction of fossil fuels. In addition, early investment in grid modernization is essential to prevent bottlenecks in the energy transition process.

What's more, the case emphasizes the importance of addressing social equity issues through "just transition" measures. Actually, the German government has established a development fund of up to 40 billion EUR to be disbursed by 2038, aimed at creating new jobs and supporting worker retraining programs in the affected coal regions [25]. The German government's measures have effectively alleviated unemployment and social injustice caused by the energy transition.

4. Pericoupling: Regional energy cooperation and cross-border challenges

Pericoupling refers to interactions between adjacent systems, which are primarily realized through regional energy cooperation. Such cooperation can involve power grid integration, the harmonization of energy policies, and the joint management of transboundary resources. These activities aim to optimize energy supply and demand across national borders.

The European Union's Energy Union exemplifies institutionalized pericoupling. It promotes the integration of energy markets by establishing a unified regulatory framework. Internally coordinated policies enable the efficient transmission of renewable energy sources, such as wind and solar, across borders, balancing regional supply and demand [26]. The Celtic Interconnector, a 575 km subsea cable, connects the electricity grids of Ireland and Brittany, France [27] . It will provide

Ireland with its first direct energy connection to continental Europe, enhancing its energy security by enabling access to France's low-carbon nuclear power.

Similarly, North America exhibits significant pericoupling dynamics through a highly integrated energy system involving the United States, Canada, and Mexico. The three countries have built an extensive network of pipelines and grid interconnections, facilitating the exchange of electricity, oil, and natural gas [28]. In 2022, Canada exported nearly 60 TW·h of hydroelectricity to the United States, providing a stable, low-carbon source of electricity, thereby improving power stability. Additionally, Mexico is a major supplier of crude oil to the United States, which in turn is the largest exporter of refined petroleum products and natural gas to Mexico [29]. This exchange compensates for Mexico's domestic refining and production shortfalls.

Although regional energy cooperation can promote integration and resource sharing, it also brings challenges. The most significant challenges are the unequal distribution of benefits and burdens, as well as policy discrepancies among countries.

Regional energy cooperation may exacerbate inequalities due to the uneven distribution of benefits and burdens. For example, within the European Union's Energy Union, Germany can utilize the integrated grid to access renewable energy sources from neighboring countries. In contrast, other member countries, particularly those in Eastern Europe, encounter significant costs associated with the coal phase-out while receiving limited financial support [30].

Furthermore, without robust multilateral coordination, regional energy cooperation is vulnerable to policy misalignments among countries. The North American energy system embodies this vulnerability. The Keystone XL pipeline, a proposed 1900 km pipeline designed to transport 830 000 barrels of oil per day, was a joint project between the United States and Canada aimed at promoting regional energy cooperation. However, disputes between the two countries over policies, including environmental standards, climate change policies, and land use, led to the cancellation of the project [31].

5. Telecoupling: Global supply chains and energy justice over distances

Telecoupling reflects how actions within one system can influence distant systems. The global energy transition generates far-reaching impacts through telecoupling, connecting distant systems via supply chains and economic flows.

The global supply chain for rare earth metals (REMs) serves as a prime example. REMs play a vital role in the production of electric vehicle motors, and China dominates the mining and processing of REMs.

In receiving countries such as those in Europe and North America, China's industrial scale has made green technologies, like electric vehicles, cheaper and more accessible, thereby accelerating their energy transitions. However, this has created supply chain vulnerabilities, where domestic policy changes or logistical bottlenecks in China can threaten the transition timelines of distant nations. In sending countries, such as China, the economic benefits and job creation are substantial [32]. However, the mining and processing of REMs have caused environmental problems, including severe water and soil pollution [33].

Simultaneously, the anticipated global decline in fossil fuel demand initiates another telecoupling process. The Organization of the Petroleum Exporting Countries (OPEC), where oil and gas revenues can constitute 60%–90% of total export earnings, is under increasing pressure to reduce its members' economic dependence on oil. In the future, it will generate significant ripple effects worldwide, whether they choose to invest in green hydrogen or adjust oil production to manage global prices during the energy transition [34]. These decisions will directly influence global energy prices and impact the economic feasibility of phasing out fossil fuels.

These transnational interdependencies have led to policy dilemmas in the global energy transition. Critical minerals, such as lithium and cobalt, are essential to produce batteries and wind turbines. These resources are concentrated in a few countries, such as Australia, and processing is carried out in countries such as China. Multinational corporations play a vital role in these supply chains. When a company invests in foreign markets, it can quickly increase mineral production. However, mining activities often result in significant environmental degradation—lithium extraction from brine in South America, for example, can use up to 2 million liters of water per metric ton of lithium produced. Although foreign direct investment can facilitate the energy transition, it often leads to an unequal distribution of benefits and burdens, with profits being repatriated while host countries endure the environmental and social costs [35].

Telecoupling research shows that the energy transition is not only a technical issue but also a geopolitical and ethical one over distances [36]. The pursuit of an efficient and fair energy transition requires a multilateral strategy that transcends national interests and upholds global justice. A truly just and sustainable energy transition requires international efforts that promote transparent and ethical supply chains and ensure fair sharing of benefits with all countries in these supply chains.

6. Challenges and policy recommendations

When viewed through the metacoupling framework, the global energy transition is a complex process with interconnected challenges and opportunities that encompasses local (intracoupling), regional (pericoupling), and global (telecoupling). This comprehensive perspective is essential for developing effective policies that can address the multi-scale challenges of the energy transition.

6.1. Cross-scale challenges

There are challenges across scales in the energy transition.

Locally, decarbonization often meets socioeconomic resistance. People in fossil fuel-dependent areas risk losing livelihoods with the phase-out of fossil fuels. In the United States, coal-dependent regions such as Appalachia have experienced job losses that have resulted in social unrest [37], demonstrating an intracoupling challenge in which domestic energy objectives conflict with local economic stability.

Regionally, cross-border cooperation has increased interdependence but also created vulnerabilities. As countries are interconnected, domestic energy security becomes a significant challenge when energy supplies from neighboring countries are disrupted. Prior to 2022, the European Union relied on Russia for approximately 40% of its natural gas supply [38]. However, severe supply disruptions experienced throughout 2022 demonstrated how energy instability can undermine regional energy security in the absence of diversified sources and robust solidarity mechanisms [39].

Globally, countries are connected through complex supply chains, which means that vulnerabilities at the local level can have global impacts. The production of essential technologies for renewable energy, such as batteries and wind turbines, depends on a limited number of critical minerals, including lithium and cobalt [40]. These minerals are mainly located in countries such as Australia and are processed in countries such as China. This poses significant risks to the supply chain because domestic policy changes or logistical bottlenecks in these key regions can lead to global supply shortages [41].

Equity considerations introduce an additional layer of complexity to the energy transition. If the benefits and burdens of the energy transition are not evenly distributed, social and global inequalities are likely to occur.

Locally, during the decarbonization process, fossil fuel-dependent areas may be left behind if not managed effectively. By replacing fossil fuels, renewable energy can mitigate the pollution in fossil fuel-dependent areas [42]. However, without retraining programs, economic compensation, and social safety nets, these regions are at risk of long-term economic decline, which could exacerbate social divides.

Globally, the "justice gap" persists. Many low- and lower-middle-income countries face significant structural challenges, including energy poverty and weak governance [43]. Compared to developed countries, many developing countries face challenges in their energy transition due to the high cost of renewable energy and limited access to financing [44]. Without sufficient international support and equitable access to capital and technology, these countries may be forced to rely on fossil fuels for longer, undermining global climate goals.

6.2. Policy recommendations

To effectively address the challenges presented by the global energy transition, a coherent, integrated policy framework is essential.

(1) Integrate the metacoupling framework into policy analysis. A foundational step is to move beyond siloed analyses and systematically integrate the metacoupling framework into energy transition policies. Policymakers should support transdisciplinary research that unites fields such as ecology, economics, energy, and sociology to address knowledge gaps regarding human–nature interactions across scales [45]. This integration must trace the complex flows of energy, materials, and finance, and develop new assessment methods that explicitly map the intracoupling (local), pericoupling (regional), and telecoupling (global) dimensions of any proposed policy.

(2) Enhance local, regional, and global collaboration. Collaboration across local, regional, and global scales is equally important.

Locally, governments must foster partnerships with businesses, academic institutions, and local communities to design transition pathways collaboratively. Collaboration includes promoting the implementation of smart grids, decentralized energy resources, and community-owned renewable energy projects.

Regionally, countries can foster the development of renewable energy by promoting cross-border projects. It is important to note that cross-border projects must be accompanied by corresponding trade regulations, coordination mechanisms, and mutual assistance mechanisms during energy crises. These measures will enhance the stability of cross-border energy cooperation.

Globally, international organizations, such as the International Energy Agency (IEA), must be empowered to promote technology transfer and mobilize finance for developing countries, thereby promoting balanced development. At the same time, communication between member countries within international organizations should be enhanced to increase the stability of supply chains.

(3) Ensure fair and just energy transitions. Locally, policymakers must implement "just transition" policies that provide robust support for fossil fuel-dependent regions. These policies should include investing in emerging green industries, funding worker retraining programs, and refining the social security system to ensure that the benefits of the energy transition are widely shared. Globally, international organizations must support developing countries through climate finance and technology-sharing agreements. In addition, countries should promote dialogue to establish transparent and ethical global

supply chains. Only by integrating justice into policy design can the energy transition benefit everyone, not just the privileged few.

In summary, it is possible to effectively address the challenges of the global energy transition by systematically applying the metacoupling framework, promoting robust collaboration, and prioritizing equity in policy design. This integrated approach combines local needs with global sustainable development imperatives, paving the way for a more sustainable future.

7. Concluding remarks

The global energy transition is characterized by deep interdependencies across local to global levels. The metacoupling framework, which comprises intracoupling, pericoupling, and telecoupling, provides a comprehensive and unified structure for analyzing these intricate mechanisms. It highlights how domestic policy choices, cross-border energy cooperation, and global supply chains are not isolated but are deeply interconnected, jointly shaping the energy transition.

By applying this framework, researchers and stakeholders can gain a clearer understanding of the interconnected challenges in the energy transition. Locally, the primary challenge in the energy transition is navigating socioeconomic resistance with proper policies, especially for the fossil fuels-dependent regions. Regionally, the growth of cross-border energy cooperation has increased interdependence, and energy security can be severely undermined during energy crises without diversified energy sources and coordination mechanisms. Globally, the energy transition is shaped by global supply chains, and vulnerabilities at the local level can have global impacts. What is more, ensuring a just transition is a challenge that needs to be considered at the local, regional, and global levels.

Confronting these issues demands an integrated strategy. First, the metacoupling framework should be integrated into policy analysis. Second, collaboration across local, regional, and global scales must be enhanced to address socio-environmental conflicts. Third, the principles of justice and equity must be embedded in the energy transition. Given the continuous changes and interconnectivity in the global energy system, our research may provide a pathway to an equitable energy transition towards a resilient and sustainable future.

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Declaration of competing interest

The authors have no competing interests to declare.