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Coal repowering in China: Beyond technology-centric perspective

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ABSTRACT

Prompted by the urgent need for a timely and orderly transition away from coal power, this paper critically examines the prospects for repowering coal-fired power plants with nuclear energy in China. While existing studies often adopt a technology-centric perspective that highlights the techno-economic potential and broader benefits of this transition pathway, this paper challenges that view by demonstrating the substantial challenges repowering faces within the broader coal-electricity regime. The analysis emphasises the importance of understanding policy, market, and governance dimensions as essential prerequisites for assessing the feasibility of coal repowering. This involves evaluating external policy pressures that compel coal power providers to adapt, as well as internal dynamics that shape their perceptions of the risks and opportunities associated with various transformation pathways. In the context of China, the viability of repowering with nuclear energy is constrained by coal generators' limited expertise in nuclear technology and their entrenched ties to other coal-sector stakeholders, including coal mining, transportation, and coal chemicals. These factors tend to direct their focus towards solutions such as carbon capture and storage, which align more closely with their existing capabilities and sustain critical elements of the coal-electricity ecosystem.

1. Introduction

Despite growing global momentum toward a clean electricity future, coal power remains a significant contributor to the world's electricity supply, accounting for roughly one-third of global generation in 2022 [1]. The urgency of addressing climate change has emphasised the need for rapid and deep decarbonisation of the electricity sector, with the transition away from coal power being pivotal to this effort [2–4]. Consequently, considerable attention has been directed toward strategies to facilitate this transition.

One such strategy is coal repowering, which involves converting existing coal-fired power plants to incorporate clean energy technologies [5]. This process typically retains key components – such as the steam cycle, condenser cooling system, and grid connections – while replacing coal boilers with technologies like small modular reactors, concentrated solar thermal systems, or geothermal systems [6,7]. In some cases, upgrades to the steam cycle are also required to integrate these new technologies [8].

A growing number of studies have explored the role of repowering in the coal power transition, suggesting that repowering is technically feasible, particularly with advancements in small modular reactors (SMRs) [9]. For instance, one study demonstrates the feasibility of converting three representative coal-fired power plants in China's coastal areas to use the High-Temperature Gas-Cooled Reactor Pebble-bed Module (HTR-PM), a domestically designed SMR [10]. Additionally, repowering has been found to be cost-efficient compared to earlier plant retirements, although its economic viability depends on factors such as plant characteristics (*e.g.,* rated capacity and equipment age) and site conditions (*e.g.,* heat sink availability and population density) [9,11]. Beyond techno-economic considerations, other studies emphasise the socio-economic benefits of repowering, including job creation and local economic development. These benefits primarily arise from repowering's ability to preserve socio-economic value embedded in existing plant facilities and grid infrastructure while contributing to decarbonisation goals [6,10,12,13].

However, existing studies have predominantly taken a technology-

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centric perspective, focusing on the technical potential, cost-effectiveness, and broader socio-economic benefits of repowering. While valuable, this approach is insufficient, as it overlooks the socio-technical dynamics that shape the coal power transition. Coal-fired power plants are embedded within a broader coal-electricity regime characterised by extensive cross-industry and cross-ownership linkages that involve coal production, logistics, coal-chemical industries, and equipment manufacturing. These interdependences cut across technical, socio-economic, regulatory, market, and governance dimensions, making the coal power transition a highly complex undertaking. Consequently, the extent to which coal repowering can garner policy and socio-political support depends not only on its techno-economic viability but also on its ability to navigate the broader complexities of the coal-electricity regime.

A broader perspective is therefore needed – one that goes beyond technology-specific considerations to account for the multifaceted nature of the coal-electricity regime. This paper seeks to address this gap by examining broader changes within the coal-electricity regime, with specific emphasis on identifying practical issues and challenges that could affect the role of coal repowering in the coal power transition. The case-in-point for this paper is provided by China, which currently hosts over half of the world's coal-fired power plants and has approximately 240 GW of new capacity currently under construction and permitted [14].

Among the various clean energy technologies that could be deployed for coal repowering – such as geothermal, bioenergy, and nuclear energy – this paper places particular emphasis on nuclear energy. There are several reasons for this choice. First, geothermal resources in China are geographically constrained, with significant reserves concentrated in southwestern provinces like Yunnan, Tibet, and Sichuan [15], limiting their widespread applicability. Second, co-firing with bioenergy offers only partial emissions reductions [16] and faces additional challenges such as feedstock availability, competition with food production for land, and land-use impacts [17]. Third, China's recent strides in SMR technology, coupled with the nation's broader priorities of energy security and technological self-reliance, make nuclear repowering a particularly promising but underexamined pathway.

The remainder of this paper is organised as follows. Section 2 reviews existing literature on the transition of the coal-electricity regime. Informed by insights from this review, Section 3 outlines the method adopted in this paper. Section 4 analyses key issues likely to affect the pursuit of coal repowering in China. Section 5 concludes the paper and discusses several policy implications.

2. Theoretical background

The ambit of transition studies has expanded considerably in recent years, as evidenced by the exponential growth of research on the subject [18]. These studies conceptualise the energy system as a socio-technical regime – an intricate network wherein technologies, human agency, and social structures converge to meet societal demands for energy, such as for industrial heating or powering electrical appliances [19]. From this perspective, the coal power transition is understood as a process of regime change, characterised by deep structural changes in coal-electricity configurations that involve multiple actors and operate across various levels and dimensions. Consequently, any examination of transition pathways – including nuclear repowering – must account for broader regime changes rather than focusing solely on technology-specific considerations (*e.g.,* technical potentials, cost-competitiveness).

To explore these complexities, the following sections examine two interrelated concepts central to understanding regime dynamics: regime inertia (Section 2.1) and incumbent diversification as a catalyst for transformative shifts within dominant regimes (Section 2.2). The relevance of these concepts to the analysis of coal repowering in China is discussed in Section 2.3.

2.1. Regime inertia

Transition studies often apply a Multi-Level Perspective (MLP) framework to analyse regime change by distinguishing between three interactive levels: niche innovations, socio-technical regime, and macro landscape [20]. According to this framework, successful technological innovations are initially nurtured within small, protected niches. Over time, as these innovations mature, they begin to challenge the dominant regime. When sufficient landscape pressures – such as shifts in public policy, market dynamics, or societal values – emerge at the macro level, these challenges create opportunities for niche innovations to break through [21], ultimately leading to a "regime shift" [22].

Despite these opportunities, dominant socio-technical regimes often exhibit significant inertia, resisting change due to the stabilisation of interdependent components such as technologies, infrastructures, regulations, and social norms [23]. This inertia sustains existing configurations and makes transformative changes a protracted process, often spanning decades. As Smil notes: "all energy transitions are prolonged affairs that take decades to accomplish" [24]. Incumbent resistance further exacerbates this inertia, as regime actors are heavily invested – both structurally and economically – in the status quo [25].

In China, incumbent coal power generators are deeply embedded in complex systems encompassing coal supply chains, engineering practices, regulatory arrangements, and policy frameworks. These interdependencies create significant lock-in effects, making transformative changes particularly difficult. Even as landscape pressures – such as global decarbonisation commitments, rising fuel costs, and growing public support for clean energy – continue to mount, regime inertia persists. This persistence is evidenced by China's continued reliance on coal generation, albeit with slower growth due to the rapid expansion of renewable energy. Factors such as sunk costs, employment dependencies, and policy incentives prioritizing energy security tend to discourage incumbents from abandoning coal-heavy portfolios and initiating transformative changes.

Empirical studies from other contexts highlight this pattern of incumbent resistance. For instance, in the context of demand-side response (DSR) policies [26], found that British incumbent generators exerted significant influence over the policy-making process regarding the inclusion of DSR in the capacity market, resulting in policy decisions that favoured incumbent interests. Similarly [27], showed that large British generators shaped the design of the capacity market through public consultations, private meetings, and commissioned modelling. Additionally [28], noted that US utilities employed various strategies to slow the growth of distributed solar PV, which they viewed as a threat to their market dominance.

2.2. Incumbent diversification

While incumbents often leverage their influence to sustain regime inertia, a more nuanced perspective recognises their potential to act as agents of change. Incumbent actors can pursue strategies to diversify into emerging clean energy sectors [29]. Diversification not only creates opportunities for value creation but also enhances the credibility of novel technologies, promotes technological variety and innovation, and facilitates knowledge and resource transfer [30].

Incumbents frequently pursue diversification in response to a confluence of financial, market, and policy changes that exert macro-level pressures for transformation [31,32]. A four-stage conceptual framework outlined in Ref. [31] describes how incumbent actors respond to such pressures. Initially, they react defensively to protect the existing regime – often constrained by lock-in mechanisms such as large sunk costs in infrastructure. As pressures intensify, some actors engage in a "local search" for solutions, leading to incremental changes, such as adopting more efficient supercritical coal power technologies. In the next stage, mounting pressures drive a "distant search" for solutions, often involving strategic reorientation toward alternative technologies such as repowering coal-fired power plants with nuclear energy. This progression ultimately culminates in an "unlocking" of belief systems, industry norms, and business models that underpin the existing regime.

While macro-level pressures act as catalyst for change, incumbents' decisions to diversify – such as repowering coal-fired power plants with nuclear energy – are often shaped by their perceptions of opportunities and challenges in emerging sectors [33,34]. These perceptions are influenced by expectations regarding the growth or decline of specific technologies [40], as well as by policy incentives designed to promote particular sectors [35]. For example, strong policy support for renewable energy can encourage coal power companies to diversify into this sector, leveraging the value-creating opportunities provided by such support.

The diversification choices of incumbents are also influenced by their capabilities [33,34]. Empirical studies suggest that incumbents are often well-positioned to diversify into "adjacent" or "related" sectors, leveraging their accumulated skills and knowledge to gain a competitive edge over new entrants [36,37]. Research indicates that firm-level diversification into related sectors tends to be more successful than diversification into unrelated sectors [38,39].

Furthermore, diversification decisions are not solely driven by individual company interests; they are also shaped by the broader actor-network supporting the dominant regime. Incumbents collaborate within extensive networks of alliances, collectives, and organisations. These networks provide them with structural power through relational networks and close contacts that enable them to influence policy outcomes [40]. Within this context, incumbents are more inclined to adopt diversification strategies that offer opportunities for other network actors to adapt, thereby minimising disruptions to industries and supply chains.

2.3. Application to the analysis of coal repowering

Fig. 1 highlights the key features of the concepts discussed above, which are highly relevant to understanding the challenges and opportunities associated with coal repowering in China. The coal-electricity regime in China is characterized by a deeply entrenched system of interdependencies spanning coal generation and mining, infrastructure, engineering practices, regulatory arrangements, and policy frameworks. This regime is dominated by state-owned enterprises (SOEs), which own and control the majority of the country's coal power assets and maintain extensive involvement in the coal industry chain, primarily through coal-electricity joint ventures [41].

These structural characteristics present significant challenges to regime change, as the stability of the entire regime depends on maintaining coal-centric operations. However, the concept of incumbent diversification offers a lens through which to explore how entrenched actors, such as generation SOEs, might drive change. Diversification enables incumbents to respond to external pressures while leveraging their existing assets and expertise.

In the context of coal repowering, incumbent diversification can be pursued as a response to major shifts in the socio-economic and policy landscapes – such as reduced financial flows for coal power assets [42], rising fuel costs that create financial challenges for coal power generators (who cannot effectively pass these costs onto end-users due to regulated tariffs), and changing market conditions resulting from the introduction of carbon pricing, which increases the costs of coal generation [43]. Additionally, growing public support for decarbonisation erodes the legitimacy of coal power [44].

These external pressures compel incumbents to consider alternative energy pathways, with options such as repowering coal-fired power plants with nuclear energy or integrating renewable technologies emerging as viable strategies. Such approaches enable generation SOEs to align with decarbonisation goals while preserving existing plant facilities and network infrastructure. The choice of diversification pathways is likely influenced by incumbents' perceptions of opportunities and challenges in emerging sectors as well as by their ability to leverage existing expertise and infrastructure. Furthermore, broader actor-networks – including alliances with coal mining companies, logistics firms, coal-chemical producers, and equipment manufacturers – play an important role in shaping diversification decisions. Repowering pathways that minimise disruptions and preserve shared interests across

Regime inertia

- Resistance to change by the dominant regime
- Causes:
  - Complex interdependencies between different regime elements (*e.g.,* technology, infrastructure, regulation, policy) that make transformative changes difficult
  - Incumbent resistance stemming from their deep attachment to the status quo

Incumbent diversification

- Incumbents are not just resisting change; they can also act as critical agents of change.
- Diversification provides a viable pathway for catalysing transformative change
- Influencing factors:
  - External pressures for change (*e.g.,* international climate commitments, introduction of carbon pricing)
  - Internal considerations:
    - ✓ Perceptions of opportunities and challenges in emerging sectors
    - ✓ Ability to leverage existing knowledge and expertise that provide incumbents with a competitive edge when entering adjacent or related sectors.
    - ✓ Influence of broader actor-networks (e.g., coal-electricity joint ventures)

Fig. 1. Regime inertia and incumbent diversification: Key features.

these networks are likely to be prioritised, ensuring stability within interconnected supply chains.

3. Method

The discussion presented in the previous section suggests a range of factors likely to influence coal repowering as a potential option for diversification. These factors can be grouped into two categories: external and internal (see Fig. 2). External factors focus on major changes in the socio-economic and policy landscapes that create pressure for change. Internal factors emphasise a range of considerations that inform the perceptions held by incumbent generators regarding opportunities and challenges associated with various diversification options, along with the actor-network underpinning the coal-electricity regime.

This paper analyses these external and internal factors in the context of China, with a view to identifying how they may influence the prospects for coal repowering through nuclear energy in the country. The data and information required for this analysis reside within historical and evolutionary accounts of China's energy sector, as well as its socio-economic background and settings. To ensure data accuracy and authenticity, a diverse range of channels have been employed to source information. These include reports and data from public agencies and governmental bodies, publications and analyses by multilateral development organisations, and peer-reviewed journals and academic studies. Similar approaches for data collection have been used in Refs. [45,46].

4. Key factors influencing coal repowering in China

This section discusses the external (Section 4.1) and internal (Section 4.2) factors likely to influence the prospects for coal repowering in China. Section 4.3 further extends this discussion by highlighting practical challenges and issues that need to be addressed to support the adoption of coal repowering in China.

4.1. External factors

4.1.1. Policy efforts to support the transition toward a renewable-based electricity future

Since 1978, China has undertaken wide-ranging and far-reaching economic reforms, transitioning from a centrally planned economic system to a more market-oriented model. These reforms, encompassing trade liberalization, foreign investment liberalization, and the modernization of state-owned enterprises, have been instrumental in driving China's remarkable economic growth. Over the course of a single generation, China has evolved from a low-income country to an upper-middle-income economy [47].

China's strong economic growth has been accompanied by a substantial increase in electricity demand, which surged from approximately 580 TWh in 1990 to over 7400 TWh in 2020 (see Fig. 3). To meet this growing demand, coal power generation expanded significantly, rising from about 440 TWh in 1990 to more than 4900 TWh in 2020. This growth has positioned China as the largest coal power producer globally, producing four times more electricity from coal than India, the second-largest producer, as of 2023 [1].

China's reliance on coal power has contributed to the provision of cheap and reliable electricity services. However, it has also led to growing air pollution and carbon emissions, highlighting the unsustainability of coal dependency. Recognising these challenges, China has stepped up its efforts to transition away from coal in pursuit of its ambitious climate goals: peaking carbon emissions before 2030 and achieving carbon neutrality before 2060.

The *Working Guidance for Carbon Dioxide Peaking and Carbon Neutrality in Full and Faithful Implementation of the New Development Philosophy* outlines the core strategies for achieving these climate objectives. This blueprint sets stringent objectives, including limiting the growth of coal consumption during the 14th Five-Year Plan period (2021–2025) and phasing it down thereafter. Furthermore, the Working Guidance emphasises strict control over the development of new coal-fired power generation projects while promoting the deployment of non-fossil energy sources – particularly renewable energy – and calls to "actively develop nuclear power in a safe and orderly manner" [49].

To translate these guiding objectives into action, the *14th Energy Five-Year Plan (2021–2025)* – China's strategic planning document for energy sector development – sets a target to increase the share of non-fossil generation to around 39 % by the end of the planning period [50]. Following this, the National Development and Reform Commission (NDRC), the country's macroeconomic planning agency, announced a detailed plan for renewable energy development in June 2022. This plan specifies targets on renewable generation and capacity utilisation (see Table 1) and emphasises the development of large utility-scale

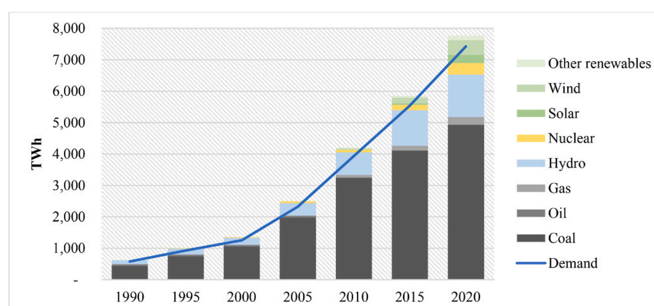

Fig. 3. Electricity supply and demand in China, 1990 to 2020.
Source: IEA (2021)

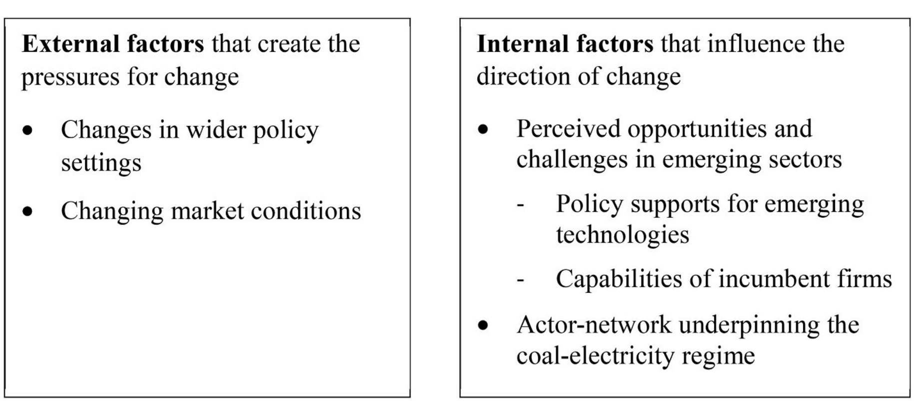

Fig. 2. Factors likely to influence coal repowering.

Table 1
Key targets for renewable energy development.

	Unit	2020 level	2025 target
Total renewable energy consumption	Billion tons of standard coal	0.68	1
Share of renewable electricity consumption	%	28.8	33.0
Share of non-hydro renewable electricity consumption	%	11.4	18.0
Renewable generation	TWh	2210	3300
Non-electric utilization of renewable energy, including geothermal heating, biomass heating and fuel, and solar heating	Million tons of standard coal	–	≥60

Source: NDRC (2022)

renewable energy bases in resource-rich western regions, complemented by distributed renewable energy systems in eastern city-clusters [51].

The release of a specific plan on renewable energy development highlights its central role in steering China toward a clean electricity future. This vision is strongly supported by major modelling studies conducted by leading Chinese energy think tanks and international organisations. For instance, a study by the Energy Research Institute of the NDRC demonstrates the feasibility of achieving a high level of renewable energy penetration rates of up to 86 % by 2050 while maintaining grid stability, with wind and solar energy serving as the primary contributors [52].

In response to the Chinese government's call for collaboration in developing energy transition pathways, the International Energy Agency (IEA) conducted a modelling study highlighting the critical role of renewable energy in achieving net zero energy emissions before 2060. The IEA projects that, by 2050, renewable energy could comprise approximately 80 % of China's total electricity supply [53]. These findings align with a more recent study by DNV, which suggests the need for a rapid expansion of variable renewable generation capacity, particularly wind and solar, through 2050. This growth is expected to be supported by a significant increase in energy storage capacity, especially after 2040. Meanwhile, the expansion of nuclear capacity is projected to remain at roughly the same levels observed during the 2010s (see Fig. 4).

4.1.2. Urgency for renewable integration

The increasing demand for system flexibility in China, driven by the growing need to integrate variable renewable generation, is reshaping the role of coal power in the country's energy landscape. System flexibility – reliably and cost-effectively managing variations in electricity demand and supply [55] – requires adequate energy storage, backup capacity, and efficient electricity markets that facilitate such flexibility [2,56].

In response, China has begun transitioning its large coal power fleet from a baseload provider to a supportive role, focusing on ancillary and capacity services for the grid. During the 2022 Two Sessions, the National Energy Administration (NEA) stated that while new coal power projects solely for electricity generation would not be permitted in

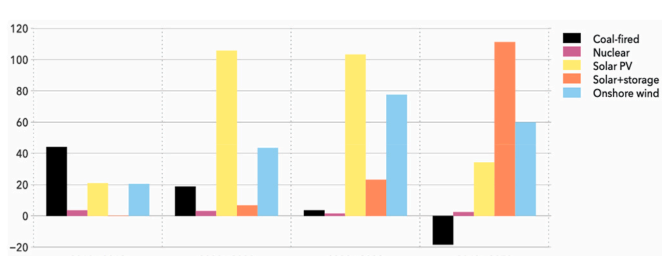

Fig. 4. Average annual capacity additions (GW/year).
Source [54].

principle, there remains scope for constructing "supportive units" of a "certain scale" to ensure supply sufficiency and reliability [57]. Additionally, the *2022 Report on the Work of the Government* emphasised transforming coal power to provide flexibility services, support higher renewable penetration, and deliver heating to reduce the use of emissions-intensive loose coal [58].

Although alternatives such as pumped hydro, battery storage, thermal storage, green hydrogen, and demand-side response are being explored, they face significant challenges – including long lead times, high development costs and strict topological requirements for pumped hydro [59,60]; high upfront costs for battery storage systems [61,62]; difficulties associated with large-scale hydrogen storage [63]; and the technological immaturity of thermal energy storage [64]. These barriers hinder their deployment at the scale required for China's accelerating renewable integration [65].

Coal power flexibilisation, as a proven and scalable technology [66], offers an immediate solution to address flexibility shortfalls. Recent power crises have underscored its importance. For instance, in 2022, a record-breaking heatwave combined with inadequate hydropower in Sichuan province overwhelmed local and adjacent power systems, leading to reduced industrial activity and electricity conservation measures [67]. Similarly, in early 2023, Yunnan experienced production cutbacks in energy-intensive industries due to low rainfall [68]. Although enhanced power connectivity could unlock additional flexibility, its implementation remains constrained by slow progress in market reforms over recent decades [69,70].

To further support coal power flexibilization, the National Development and Reform Commission (NDRC) introduced a capacity payment mechanism in 2023 [71]. This initiative was designed to address the severe financial challenges faced by coal power generators due to high fuel costs – which led to losses of 120 billion yuan (approximately US$16.6 billion) in 2021. Although conditions improved somewhat in subsequent years, cumulative losses still exceeded 10 billion yuan (approximately US$1.4 billion) in the first half of 2023, with some plants bearing debt ratios above 75 % [72]. Under the new scheme, coal-fired power plants receive a monthly capacity payment of 100 yuan/kWh, with a higher rate of 165 yuan/kWh for plants located in provinces with higher shares of clean energy generation. Plants failing to meet national standards for flexibility, efficiency, or environmental performance are excluded from these payments [71].

While the long-term impact of the current coal-specific capacity payment mechanism on repowering incentives remains uncertain, it has, along with lower fuel prices, helped alleviate short-term financial pressures on coal power generators. In the first half of 2024, the five major central generation SOEs – Huaneng, Huadian, Datang, State Power Investment Corporation, and China Energy – achieved a turnaround, collectively posting profits exceeding 23.3 billion yuan (approximately US$3.2 billion) [73]. The capacity payment scheme, by compensating generators for providing capacity rather than electricity, aligns incentives with maintaining grid reliability rather than maximising output, thereby enabling a focus on flexibilisation.

International experience suggests that technology-neutral capacity payment mechanisms are more effective in delivering capacity services while fostering innovation and competition among different flexibility options. For example, studies on the UK's Capacity Market demonstrate how technology-neutral auctions incentivise a diverse mix of technologies – including demand-side response, battery storage, and gas peakers – to compete on equal footing, thereby optimising the system for cost-effectiveness and environmental performance [74]. Adopting a similar framework in China could create competitive pressures on coal power generators, encouraging them to explore cleaner and more distant decarbonisation options such as repowering.

4.2. Internal factors

4.2.1. Policy support for renewable energy and energy storage sectors

Prior to 1985, China's electricity industry was publicly owned, vertically integrated, and operated through State-Owned Enterprises (SOEs) under the administrative supervision of the Ministry of Electric Power Industry (MEPI). Beginning in 1997, major steps were taken to separate government functions from the operational management of publicly owned energy enterprises, addressing concerns over poor financial performance [75]. A key milestone in this process was the establishment of the State Power Corporation (SPC) in 1997, which assumed operational responsibilities from MEPI and acquired electricity assets from local Bureaus of Electric Power (BEPs) [76].

Further restructuring ensued in 2002, with the SPC's generation assets divided among five major companies, namely, Huaneng, Huadian, Guodian, Datang, and China Power Investment [76]. Subsequent mergers and acquisitions solidified the dominance of these SOEs, commonly referred to as the "Five Bigs and Four Smalls". While Three Gorges Corporation and China General Nuclear Power are exceptions, the majority of SOEs hold significant coal power assets.

In recent years, major SOEs have increasingly diversified into the renewable energy sector. This shift has been facilitated by the establishment of dedicated subsidiaries, with substantial capital expenditure (capex) allocated to renewable energy projects [77]. SOEs have also emerged as key investors in battery storage projects. As of June 2023, there were 325 battery storage projects under construction in China, with nearly half supported by the "Five Bigs" [78].

These trends are closely tied to strong policy support for renewable energy and energy storage as well as the perceived opportunities these sectors offer. The *13*th *Five-Year Plan for Renewable Energy*, issued by the NDRC in 2016, set a target to achieve 680 GW of renewable energy capacity by 2020 [79]. The target was supported by generous feed-in tariffs (FiTs), access to capital from policy banks, and other financial incentives [80]. Starting in 2021, FiTs have been gradually phased out for new wind and solar projects and replaced with market-based incentives, including competitive auctioning, voluntary green certificate trading, and renewable portfolio standards [81].

In energy storage, the NDRC released policy guidelines in 2021 to expedite development, targeting over 30 GW of non-hydro energy storage capacity by 2025 [82]. Subsequently, more than 20 provinces announced plans to deploy energy storage systems with a combined capacity exceeding 40 GW [83].

4.2.2. Lack of capabilities related to nuclear energy

The limited involvement of most generation SOEs in operating nuclear power plants highlights their insufficient nuclear energy capabilities, posing significant challenges to pursuing coal repowering via nuclear energy.

Nuclear power generation in China is dominated by three specialised SOEs: China National Nuclear Corporation (CNNC), China General Nuclear Power Group (CGN), and the State Power Investment Corporation (SPIC). Established in 1988 from the Ministry of Nuclear Industry, CNNC oversees both civilian and military nuclear activities [84]. It operates across the entire nuclear energy supply chain, including uranium mining, fuel fabrication, reactor design and construction (following its merger with the China Nuclear Engineering & Construction Corporation in 2018), and nuclear waste disposal [85]. Initially focused on nuclear power in Guangdong province, CGN has progressively expanded into other regions and diversified into renewable energy projects [86]. Through its subsidiary, the State Nuclear Power Technology Corporation, SPIC is primarily engaged in developing the third-generation nuclear power technologies [86].

Notably, CNNC and CGN do not manage significant coal power assets, reflecting the historical separation between coal and nuclear power sectors. SPIC, while involved in both coal and nuclear power, has relatively minor coal-related operations compared to major coal-heavy SOEs. This situation underscores significant constraints faced by coal-heavy SOEs, such as Huaneng, Huadian, Datang, and China Energy, in pursuing nuclear-related projects, including coal repowering through nuclear energy. Key challenges are discussed below:

Nuclear expertise: Most coal-heavy SOEs have not developed the supply chains, partnerships, or in-house expertise required to design, construct, and operate nuclear power reactors. Repowering via nuclear energy entails stringent regulatory and safety requirements that demand long-term planning and specialised knowledge.

Institutional fragmentation: Historically, coal-heavy SOEs operated within a coal-electricity regime with limited exposure to nuclear activities. In the 1950s and 60s, China's electricity sector was predominantly coal-based due to abundant coal reserves; nuclear power was entirely absent from the generation mix, and nuclear organisations were not integrated into the coal-electricity regime. Early discussions on nuclear energy focused primarily on military applications rather than on civilian energy uses [85].

The 1970 power crisis in Shanghai rekindled interest in nuclear power, but institutional inertia hindered progress. Key nuclear agencies, such as the Second Ministry of Machine Building (later the Ministry of Nuclear Industry), resisted shifting their focus to civilian applications. Meanwhile, the Ministry of Electric Power Industry (MEPI) was sceptical of nuclear power, citing high costs and technological risks [85].

It was not until 1978 that the central government formally announced plans for civilian nuclear power development. However, persistent misalignment between the Ministry of Nuclear Industry and MEPI continued into the 1980s, delaying the establishment of a cohesive nuclear power development strategy [84]. By 1996, nuclear power accounted for only about 1 % of China's electricity generation [48]. Currently, nuclear generation is dominated by three specialised SOEs. This structural isolation has reinforced silos, preventing cross-sector collaboration and the transfer of nuclear expertise.

Strategic priorities: The reliance of coal-heavy SOEs on established coal portfolios further limits their interest in diversifying into the nuclear power sector via repowering. Their existing business models and infrastructure are tailored to coal-based operations, and the high capital costs, long payback periods, and complex risk profiles associated with nuclear energy make such a transition less attractive compared to a renewable-based diversification strategy, which may allow these SOEs to address short-term flexibility needs with only limited retrofitting.

4.2.3. Actor-network underpinning the coal-electricity regime

Coal power in China is deeply embedded within a complex coal-electricity regime characterised by extensive interconnectedness across regions, industries, and ownership structures. This network integrates coal mining, power generation, transportation, and related industries such as coal chemicals and metallurgy, creating a deeply entrenched system that poses challenges to repowering initiatives.

In the early 2000s, large generation SOEs made significant investments in coal production to enhance coal self-sufficiency. Collaborative efforts between electricity companies and coal enterprises fostered the development of coal chemical and metallurgy industries, as well as coal logistics, leading to an integrated coal-electricity supply chain [41]. Starting in 2015, the supply-side structural reform, aimed at reducing overcapacity in coal generation, further consolidated coal and electricity assets. Notably, in 2017, the merger of Shenhua Group, China's largest coal mining company, with Guodian, one of the country's largest generators, created China Energy Investment Corporation. This vertically integrated entity now operates across the entire supply chain, from coal mining to power generation [87].

In coal-rich provinces, such as Shanxi, Shaanxi, Inner Mongolia, and Xinjiang, a growing trend has emerged toward constructing large-scale coal-fired power plants adjacent to coal mines. These plants primarily cater to the electricity demands of eastern city-clusters via ultra-high voltage transmission lines [88]. By the end of 2021, coal companies collectively owned over 340 GW of generation capacity, representing more than 30 % of the country's total coal power capacity [89]. In provinces with less significant coal resources, mergers and acquisitions primarily involved local coal and energy companies. These efforts, actively supported by local governments, have aimed to establish stronger provincial electricity groups and increase local influence in electricity markets.

The interconnectedness of coal-dependent industries and the consolidation of coal and electricity assets present substantial obstacles to repowering efforts. Key challenges include:

Interdependence of industries: The integrated nature of the coal-electricity regime creates significant resistance to repowering initiatives, as transitions may disrupt supply chain activities (*e.g.,* equipment manufacturing, coal transportation) and adversely affect local economies reliant on coal mining.

Misaligned priorities: Central and local SOEs may have conflicting priorities; local entities often prioritise economic stability and employment, while central authorities emphasise national energy strategies. This misalignment hinders consensus among stakeholders – a prerequisite for implementing repowering projects.

Entrenched investments: Decades of investments in coal-based assets have entrenched the coal-electricity network, creating significant barriers to shifting to alternative energy sources. The sunk costs associated with power plants, logistics networks, and industrial facilities discourage SOEs from pursuing alternatives such as nuclear or renewable repowering.

4.3. Discussion

Based on the discussion above, several key issues affecting the feasibility of pursuing coal repowering in China can be identified:

Lack of awareness in current policy settings: China's current policy landscape predominantly emphasises building a clean power system with renewable energy as its backbone, supplemented by storage technologies and more flexible market trading mechanisms (see Section 4.1.1). While nuclear energy is acknowledged as a vital complement to renewable energy, its development is focused on capacity expansion in coastal areas, rather than integrating it into coal repowering initiatives. For example, the 14th *Five-Year Plan* aims to "actively, securely and steadily" advance coastal nuclear power construction, with a target of reaching a nuclear power installed capacity of 70 GW by 2025 [50] – an approximately 25 % increase from 2022 levels (56 GW). The plan also prioritises advanced nuclear technologies, including third-generation reactors (Hualong One, and Guohe One) and high-temperature gas-cooled reactors, with a demonstration project in Shandong showcasing China's first fourth-generation reactor [80].

However, coal repowering via nuclear energy has yet to receive significant policy attention. This lack of awareness cannot be solely attributed to insufficient information or knowledge. Several systemic factors contribute to this situation, as discussed below.

Policy support **for coal power flexibilisation**: China's growing reliance on renewables has heightened the need for system flexibility to manage intermittency (see Section 4.1.2). Coal power, as a proven and scalable technology, provides an immediate solution – especially given the limitations of alternatives (*e.g.,* battery storage, green hydrogen, pumped hydro). Policies such as capacity payments to coal power generators alleviate short-term financial pressures but may delay the exploration of longer-term decarbonisation solutions such as nuclear repowering.

Influence of individual and collective interests: President Xi Jinping's 2021 announcement to "strictly control coal consumption" until 2025 and "phase down coal consumption thereafter" highlights the growing pressure to reduce emissions. This policy signals a shift in priorities, prompting coal generation SOEs and their upstream counterparts to seek diversification strategies. However, their choices and preferences are shaped by individual and collective interests within the coal-electricity regime.

China's energy governance is characterised by fragmentation, involving central ministries, SOEs, local governments, and other stakeholders. This fragmentation creates diverse and often conflicting interests, complicating the decision-making process [90]. Central directives must balance localised considerations (such as economic stability and employment) with national energy strategies. Successfully navigating these dynamics requires collaborative and inclusive governance mechanisms to reconcile differing perspectives and address underlying trade-offs.

The interplay between central directives and local considerations further illustrates that facilitating change within the coal-electricity regime is not a top-down process. Instead, it relies on a complex negotiation process where decisions are shaped by sectoral and regional interests. Within this context, coal repowering initiatives must be articulated alongside other diversification options with careful attention to the interdependence and competing priorities involved. For example, as detailed in Section 4.2.2, only three SOEs in China (namely, CNNC, CGN, and SPIC) operate nuclear power assets. Among these, CNNC and CGN are not involved in coal generation, while SPIC primarily focuses on third-generation reactor development. This limited nuclear expertise among coal-heavy SOEs (*e.g.,* Huaneng, Huadian, Datang, China Energy) makes integrating nuclear energy into their portfolios particularly challenging. Instead, these entities are more likely to explore solutions that align with their existing capabilities.

Furthermore, China's coal-electricity regime is an intricate network encompassing coal production, power generation, coal chemicals, and equipment manufacturing. A reduction in coal generation resulting from repowering could lead to a decline in coal mining activities, adversely impacting industries such as equipment manufacturing and transportation, and disrupting local economies. Consequently, stakeholders across the coal-electricity supply chain may resist initiatives that threaten their established business models.

5. Conclusions and policy implications

This paper develops a broader perspective on the prospects for coal repowering via nuclear energy in China – moving beyond technology-centric considerations such as technical potentials, economic viability, and externalities (*e.g.,* local economic impact). The findings highlight a general lack of awareness and prioritisation of coal repowering within China's current policy settings, which remain focused on establishing a clean power system centred around renewable energy, supplemented by storage technologies and flexible market mechanisms. While nuclear energy is acknowledged as a vital complement to renewables, its development has been concentrated on capacity expansion in coastal areas, leaving coal repowering via nuclear energy largely overlooked.

This lack of attention is not merely due to information gaps; systemic factors play a significant role. For example, capacity payments to coal generators ease immediate financial pressures and delay the exploration of more distant diversification options, such as nuclear repowering. As decarbonisation pressures mount in China, it is very likely that coal-based SOEs and their interconnected entities will begin exploring further diversification strategies. However, their limited nuclear expertise suggests that repowering may not be their immediate priority – instead, collective interests may steer them towards options like carbon capture and storage (CCS), which better align with the existing coal-electricity ecosystem.

This paper does not advocate for or against nuclear energy. Rather, it underscores the urgent need to manage the decline of the coal-electricity regime to mitigate the most severe impacts of climate change. According to the IEA's Net Zero Emissions by 2050 Scenario, the phase-out of all unabated coal generation is required by 2040 to achieve the Paris climate goals of limiting global warming to 1.5 °C [91] – a timeline that signals the impending decline of coal generation and its associated ecosystem.

Repowering offers a potential pathway to manage this transition, especially amid technological uncertainties. For instance, if CCS deployment continues at its current pace, global carbon storage capacity by 2050 would reach only 700 million tons annually – just 10 % of the required level [92]. In such a scenario, repowering could serve as a critical fallback option to accelerate the decarbonisation of China's energy system.

Preparing for this transition necessitates a shift away from a narrow, technology-centric focus toward a broader perspective that considers policy, regulatory, market, and governance issues within the coal-electricity regime. This paper represents an initial step in broadening the discussion, emphasising the importance of addressing these systemic dimensions to unlock the full potential of coal repowering. Future research should explore in greater depth the factors driving incumbent diversification and how incumbents evaluate and prioritise options such as repowering via nuclear energy.

Additionally, the pursuit of coal repowering via nuclear energy faces not only systemic and operational challenges but also nuclear-specific concerns. Social concerns surrounding nuclear waste management and the reliance on uranium imports raise questions about the long-term sustainability and energy security implications of such projects. Although not discussed in detail here, these issues are critical and warrant further exploration as they will likely shape the feasibility and attractiveness of coal repowering through nuclear energy.

CRediT authorship contribution statement

Muyi Yang: Conceptualization, Methodology, Writing – original draft, Writing – review & editing. **Yadong Wang:** Data curation, Formal analysis, Investigation. **Xunpeng Shi:** Writing – original draft, Supervision, Funding acquisition. **Philip Andrews-Speed:** Writing – Review. **Jiahai Yuan:** Writing – Review. **Deepak Sharma:** Writing – Review.

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.

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Data availability

No data was used for the research described in the article.

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