Engineering 65 (2026) 183–197

Contents lists available at ScienceDirect

Engineering

journal homepage: www.elsevier.com/locate/eng

Research
Energy Transition's Technical Pathways, Risks, and Equity—Article

Properly Positioning Coal Power in Decarbonizing the Global Power Systems

Jinze Li [a], Fang Fang [a,*], Yuanye Chen [a], Songyuan Yu [a], Jizhen Liu [a,b,c], Yanjun Du [a], Ming Du [a,c], Yi Zhang [a], Qinghua Wang [b], Yuguang Niu [b,c]

[a] School of Control and Computer Engineering, North China Electric Power University, Beijing 102206, China
[b] National Key Laboratory of New Energy Power Systems, Beijing 102206, China
[c] Beijing Huairou Laboratory, Beijing 101499, China

ARTICLE INFO

Article history:
Received 6 October 2024
Revised 17 May 2025
Accepted 11 June 2025
Available online 19 June 2025

Keywords:
Coal power flexibility
Energy transition
Flexibility option
Flexibility economic

ABSTRACT

Coal-based electricity generation stands as the largest single source of global carbon dioxide emissions. The United Nations Climate Change Conference 28 (COP28) reached a historic consensus by all parties to transition away from fossil energy. On a global scale, a tripling of renewable energy capacity and a doubling of energy efficiency improvements by 2030, while gradually phasing out unabated coal power. As we move toward a decarbonized power system in a just, orderly, and equitable manner, coal power can enhance the integration of renewable energy into the electricity system by providing flexible services such as rapid ramping, cycling, and reliable capacity backup, ensuring the secure and stable operation of the system. Herein, we contribute to clarifying the role of coal power flexibility in the different phases of renewable energy development. By analyzing the metrics and costs of coal flexibility, we find that flexibility retrofitting can improve the regulatory capacity of the power system, reduce carbon emissions, and provide economic benefits for operators. The research findings emphasize that coal flexibility can positively contribute to decarbonization through policy support and technological innovation.

© 2025 THE AUTHORS. Published by Elsevier LTD on behalf of Chinese Academy of Engineering and Higher Education Press Limited Company. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).

1. Introduction

To keep global warming within reach of the Paris Climate Agreement, there is a strong voice to phase out coal power rapidly [1–3]. The Intergovernmental Panel on Climate Change (IPCC) of the United Nations has released its Sixth Assessment Report (AR6) based on extensive academic evidence. The report shows cutting down half of the emissions through phasing out coal power by 2030 [4–6]. Since United Nations Climate Change Conference 27 (COP27), a debate has been on phase-down versus phase-out of unabated coal. However, a series of energy security events in the past three years have made the outcome of this debate clear [7]. Europe's energy market experienced a grave crunch in 2022 [8]. China also experienced widespread rolling blackouts due to the significant impact of extreme weather on renewable energy generation in 2021, such as hydro and wind power. These facts negate the viewpoint of completely phasing out coal power.

In 2023, 70% of the total global coal consumption was used for power generation [9]. The high carbon emission intensity of coal power and its substitutability in the energy structure are the main reasons why the IPCC hopes to phase out coal-fired power [10,11]. However, the importance of coal-fired power generation varies greatly among countries at different stages of development. Constituting 26% of electricity generation in high-income countries and 49% in low- and middle-income countries, an overemphasis on expeditious coal phase-out as the principal mitigation measure may create an unjust narrative [10,12]. Therefore, the consensus reached at COP28 calls for reducing unabated coal power, eliminating ineffective fossil fuel subsidies, and implementing other measures supporting a transition from fossil fuels in energy systems. This transition is advocated to be executed in an equitable, just, and orderly manner, with developed nations maintaining their role as pioneers [7].

The penetration of high-share variable renewable energy (VRE) is crucial for achieving decarbonization and climate mitigation goals. However, the intermittency and uncertainty of VRE can significantly impact operational stability and power supply, directly threatening residential electricity safety and national energy

* Corresponding author.
E-mail address: ffang@ncepu.edu.cn (F. Fang).

https://doi.org/10.1016/j.eng.2025.06.019
2095-8099/© 2025 THE AUTHORS. Published by Elsevier LTD on behalf of Chinese Academy of Engineering and Higher Education Press Limited Company.
This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).

security [13,14]. Developed regions have sufficient capacity reserves to accommodate the growing VRE share, while others lack window periods to leap forward. Therefore, a rational view is that during the transition, coal power can serve as a capacity supply and flexible regulating tool to facilitate VRE, thus contradictorily contributing positively to decarbonizing the power systems.

Traditional coal-fired power plants (CFPPs) are known for providing stable base-load power. Compared to other types of power plants, such as natural gas and nuclear, CFPPs still dominate in many countries, notably those that heavily rely on coal in their energy mix [15,16]. We also recognize that natural gas and nuclear power plants are less carbon-intensive options. They possess potential advantages in providing flexibility to power systems, with many developed regions already effectively utilizing these technologies [17]. While natural gas power plants offer high flexibility, the uneven distribution of resources and price volatility limit their reliability as a primary option in certain areas [18]. Due to its technical characteristics and safety requirements, nuclear power faces challenges with frequent start-ups or rapid output adjustments [8]. Although emerging energy storage systems such as lithium-ion batteries, flywheel energy storage, and supercapacitors offer fast response times and precise regulation, they are limited by technology and high capital costs and cannot provide high-capacity regulation capabilities. In contrast, upgrading coal power flexibility is a more mature technological approach. It allows for retrofitting existing infrastructure, avoiding the high costs and lengthy timelines of building new power plants. The flexibility retrofit of CFPPs is achieved through equipment upgrades and optimization of operational strategies. This transformation shifts coal-fired power units from a base load position to flexible resources capable of providing rapid ramping, deep peak-shaving, and frequency response through technical and management measures. Furthermore, the widespread availability of coal resources globally simplifies the upgrading of CFPPs for flexibility, meeting the energy transition's short- and medium-term needs [19].

The flexibility exhibited by coal power pertains to the capacity of coal-fired units to accommodate substantial fluctuations in output and promptly react to diverse changes [20]. Several key factors can define and measure coal power flexibility, including operational flexibility like ramping, cycling, capacity backup, fuel flexibility, and carbon capture and storage (CCS) retrofitting. The additional benefits of suitable market mechanisms and ancillary services can promote CFPPs to invest in the research and development of flexible technologies [21]. Compared to much of the theoretical literature on the complete elimination of coal power, the role of coal power flexibility in the orderly decarbonization transformation process is underestimated. In discussing underappreciated linkages, we work from a definition of flexibility as a techno-economical norm. We have outlined the role of coal-fired power unit flexibility in countries at different phases of renewable energy development. Summarized the flexibility indicators and technical methods to enhance flexibility and analyzed the operating costs and associated benefits. Thus, contributing valuable insights for nations/jurisdictions transitioning from coal-based to renewable power systems.

The full text conducts a multidimensional analysis from policy, economy, and technology perspectives to explore the role of coal-fired power flexibility in promoting VRE penetration. Integrating fragmented and discrete relevant information has improved the comprehensiveness of research on coal-fired power flexibility and its decision-making reference value. The application of global comparative methods enhances the universality of research conclusions. Explore the impact of coal-fired power flexibility on energy security and equity characteristics. Key directions for future research have been identified, providing theoretical support for the flexible modification of CFPPs. The remainder of this paper is organized as follows. Section 2 elaborates on the methods employed in our study, including literature review, data collection and analysis, policy assessment, technological options, and cost–benefit analysis. Section 3 presents the role of coal power flexibility at various phases to emphasize its importance in maintaining grid stability and facilitating the energy transition. It also discusses relevant countries' market responses and policy support regarding coal plant flexibility. Section 4 summarizes the key indicators for assessing coal power flexibility and analyzes the technical options for enhancing flexibility through plant retrofitting. We propose the costs and potential benefits associated with improving flexibility in Section 5. Further discussion on establishing the correct value orientation for coal power flexibility is provided in Section 6. Finally, the main conclusions of this paper are presented in Section 7.

2. Methodology

2.1. Selection and analysis of countries

We gather energy structure data from 13 major countries, comprising 8 developed and 5 developing countries. These countries represent 9 out of the top 15 countries in global gross domestic product (GDP) rankings (the United States, China, Germany, Japan, India, United Kingdom, Italy, Mexico, and Republic of Korea); 7 of the world's top 10 coal consumers (China, India, United States, Japan, Republic of Korea, Germany, and Vietnam). In addition, Denmark and Ireland, which are pioneers in the transition to decarbonization, are also included. The share of coal-fired power generation in these countries ranges from over 70% in India to 0 in Denmark, covering phases 1–6 of the VRE integration. For instance, Indonesia and India have a high proportion of coal-fired power (over 60%), placing them in the early phases of VRE integration (phases 1 and 2). In contrast, Denmark boasts a high proportion of VRE (over 80%) in the deep integration phase (phase 5). These phases exhibit significant differences in flexibility requirements. The diversity and richness of the energy structures among these countries render them highly representative, providing strong comparability for analysis. Integrate advanced representative country Denmark; the mature integration phase represents countries such as Italy, Germany, Ireland, and United Kingdom; the transitional phase represents countries such as China, United States, Japan, and so forth. In the early phases, it represented countries such as Republic of Korea, Vietnam, Indonesia, among others. The division and description of different stages refer to Table 1 [22].

2.2. Statistical and analytical assessment of policy status

We analyze the policy frameworks of various countries aimed at promoting the flexible retrofit of coal power generation. This includes national or international financial and tax incentive measures, carbon pricing mechanisms, market incentive policies, and specialized regulatory policies. The incentives and constraints of these policies on coal power flexibility retrofitting vary significantly. In some countries, policies directly provide financial support and policy-driven benefits for the flexible retrofitting of CFPPs, such as peak shaving subsidies in China. In contrast, other countries indirectly encourage flexibility retrofitting through mechanisms like carbon emission trading or renewable energy quotas, as exemplified by Japan's carbon tax. This analysis highlights the different levels of attention and strategic focus that various countries place on coal power flexibility. It offers valuable insights for countries with less-developed approaches in this area.

Table 1
Different phases of VRE integration in the power system [22].

Phase	Phase status	Phase description	Countries/regions
1	System integration is not a relevant issue	The first batch of VRE power plants has been deployed. Still, their impact on the system level is very localized and basically negligible, for example, at the connection point between the power plants and the power grid	Republic of Korea, Indonesia
2	Draw on existing flexibility	With the increase of renewable energy power plants, the variation between load and the net load becomes pronounced. Upgrading operational methods and using existing system flexibility resources is usually sufficient to achieve system integration	United States, Japan, India, Vietnam
3	Flexibility investment in all measures	The more significant fluctuations between electricity supply and demand have prompted a system-level increase in flexibility, but this exceeds the flexibility that existing assets and operational methods can provide	European Union, China, Mexico
4	Require advanced technologies	Renewable energy sources provide most of the electricity demand during specific periods (with a high proportion of renewable energy generation at low demand), and frequency response services must be provided to promote power system stability	Italy, Germany, United Kingdom, Ireland
5	Frequent periods of VRE exceeding demand	Adding more renewable energy power plants means that their production capacity often exceeds electricity demand, creating a structural surplus of negative net load, leading to an increased risk of renewable energy curtailment	Denmark
6	VRE causes excess or deficit over months and seasons	The main obstacle to achieving a higher proportion of renewable energy generation is meeting net load demand during periods of insufficient wind and solar energy supply, requiring seasonal storage methods to adjust the supply and demand balance	—

2.3. Summary and analysis of technological progress

Assessing technological options is a critical component of this study. We analyze and compare various flexibility evaluation metrics. A detailed discussion of technological approaches to enhancing flexibility across the coal power generation system, including optimizing and upgrading subsystems. For example, combustion system optimization, control system upgrades, material and structural improvements, energy storage technology integration, and CCS technology. The maturity and application of different technological pathways vary. Some technologies, such as boiler combustion optimization and control system upgrades, are relatively mature and widely implemented. In contrast, emerging technologies like energy storage integration and CCS are still in the demonstration project phase but show significant potential for future development and application. We evaluate the direct impacts of these technologies on coal power flexibility and their associated constraints.

2.4. Economic benefits analysis

In analyzing economic benefits, we examine the costs associated with coal power flexibility and the corresponding subsidies or revenue streams. Using a multidimensional analytical approach incorporating the policy environment, market mechanisms, and technological advancements of different countries, we conduct a comprehensive assessment of economic returns. In countries with high shares of renewable energy, such as Denmark and Germany, the financial benefits of coal power flexibility primarily stem from frequency regulation and reserve services. Conversely, in coal-dependent countries such as China and Vietnam, the benefits mainly come from enhancing peak-shaving capacity and subsidy revenues. These analyses provide scientific evidence to support policymakers and business decision-makers in advancing initiatives for retrofitting coal power flexibility.

2.5. Equity analysis

Conducting a multidimensional analysis is essential for evaluating the equity of coal power. This approach considers a broad range of factors, including technical, economic, policy, market, social, and environmental aspects, while accounting for differences in VRE integration phases, resource endowments, and national development levels. Developed countries, such as Germany and Denmark, have well-established energy infrastructures and robust technological innovation capacities, with high shares of VRE in their energy mix. Conversely, developing countries, such as Vietnam and Indonesia, rely more heavily on coal power within their energy structures and possess relatively weaker electricity infrastructures. Nevertheless, as renewable energy advances, these countries are expected to encounter drastically increased flexibility demands, making retrofitting coal power plants for flexibility an urgent priority in the near future.

2.6. Sources of literature and data

This step provides the theoretical foundation and international comparative perspective. Guiding the collection and analysis of global and regional data to illustrate the current status and potential of coal power flexibility retrofitting. The data sources for policies consist of national policies (gathered from the official websites of energy departments and legislative bodies across various countries), regional market rules (sourced from European Network of Transmission System Operators for Electricity (ENTSO-E) and California Independent System Operator (CAISO) for electricity market operation documents), and international cooperation databases (integrated with International Renewable Energy Agency (IRENA) policy tracking platform and Renewable Energy Policy Network for the 21st Century (REN21) global renewable energy policy database). Economic data sources include cost and benefit data (related policy subsidies issued by various official sources and annual reports of electricity exchanges in multiple countries) and electricity market data (collecting China Electricity Council data and US Pennsylvania–New Jersey–Maryland (PJM) market electricity prices).

3. The role of coal power flexibility in different phases

This section focuses on the role of coal power flexibility at different stages. It aims to analyze how to support the integration of VRE. First, we discuss the challenges of fully integrating VRE and highlighting the growing demand for flexibility in power systems during the transition. Next, we examine how countries adapt coal power flexibility to their VRE development phases. This includes technological upgrades, market mechanisms, and policy incentives. Specifically, we analyze how Southeast Asian, American, and European countries promote coal power flexibility based on their distinct energy structures. Additionally, we present

case studies to explore different regions' challenges and practical experiences in enhancing coal power flexibility. This structured analysis helps clarify the global adaptation patterns of coal power flexibility and provides theoretical support for optimizing future energy systems.

3.1. Barriers to 100% VRE integration

In global decarbonization efforts, coal power generation still plays an indispensable role in the energy transition, particularly in the short term. While wind and solar are commonly viewed as the primary future energy sources, their inherent characteristics of low energy density and intermittency make achieving 100% VRE integration unfeasible in the short term [23]. Flexibility is crucial, as coal power plants maintain grid stability and respond to demand fluctuations. Wind and solar power generation depend on weather and seasonal variations, complicating efforts to ensure a stable power supply [24]. Grid reliability is another significant challenge. Although energy storage systems and smart grids can partially mitigate this problem, current energy storage technologies remain immature and costly. They cannot fully replace the continuous power supply provided by traditional power sources [25]. Furthermore, the low energy density of renewable energy means that large areas of land or marine space are required to install renewable energy infrastructure [26]. In some regions, this is limited by scarce land resources and environmental protection regulations. Therefore, despite the critical role of renewable energy in decarbonization, these technological, economic, and geographical challenges render it unrealistic to achieve 100% VRE integration in the short term. Coal power flexibility can be vital during this transitional period [27].

3.2. Coal power flexibility demand

The changes in electricity demand and supply could increase the need for flexibility providers in power systems [28]. This indicates that flexibility has become a new slogan for power safety. In the stated policies scenario (STEPS), the flexibility of the global power system needs to more than double by 2050. In the announced pledges scenario (APS), flexibility doubles by 2030 and increases by 3.5 times by the end of 2050, while in the net zero emissions (NZE), flexibility needs to increase by more than four times from current levels to 2050 (Fig. 1) [29]. In the techno-economic literature, the increase in renewable energy is related to the growing demand for ramp up. However, each region's geography and local conditions have a series of flexible sources and convergence points, influencing the strategies adopted alongside broader policy and economic trends [30]. Therefore, the solution varies with different requirements. Different flexibility resources help meet the flexibility requirements of a given system (Fig. 2) [31]. However, in the entire prospect, coal power remains the cornerstone of system flexibility. Renewable energy enhances the variability of net demand [32], allowing power plants to deliver a range of basic flexibility services based on their ability to adjust output, particularly concerning maintaining a stable minimum level of output (minimum load), the rate of change in power output (ramp rate), and the duration of startup or shutdown.

3.3. Different phases of VRE integration

In recent years, the rapid development of clean energy has led to major changes to the power and grid structures. The large-scale, centralized grid connection of renewable energy has made

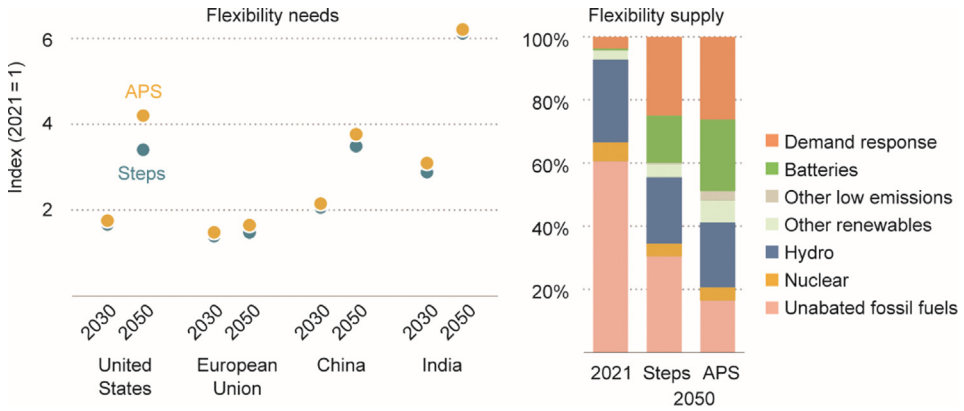

Fig. 1. Flexibility demand and supply by region and scenario [29].

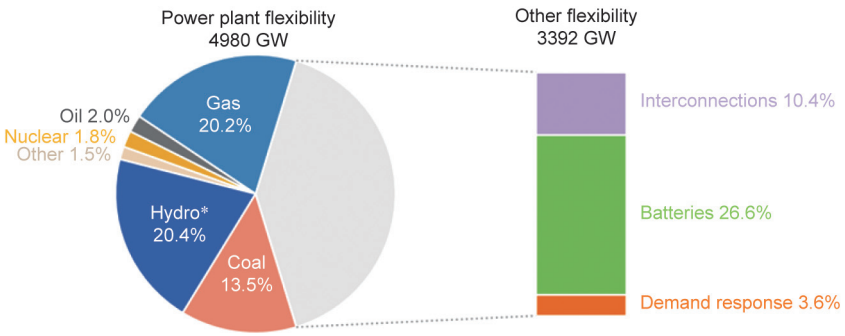

Fig. 2. Potential contribution of flexibility resources [31].

peak and frequency regulation more challenging. In some regions, issues such as curtailing renewable energy, restricting nuclear energy, system peak regulation, and contradictions between electricity and heat in the heating season are prominent. However, the integration challenges may escalate with continued renewable expansion to achieve the decarbonization goals, yet could be mitigated by increasing system flexibility. Different actions are required through different phases. The International Energy Agency (IEA) divides the integration of VRE into six distinct phases, as illustrated in Table 1 [22].

3.4. Polices in different countries' phases

According to the six distinct phases proposed by the IEA, Fig. 3 illustrates the continually evolving flexibility requirements in the integration process of renewable energy across 13 representative countries/regions worldwide [31]. The role of coal-fired power flexibility differs among countries, based on their phase of renewable energy development. Moreover, we have sorted out the policies issued by some countries during their respective periods of coal-fired power transformation in Table 2 [33–52], including relevant provisions that directly target the flexibility transformation of CFPPs and policies that indirectly guide their flexibility upgrades.

3.5. Phases of different countries

The current sample of 13 countries covers administrative mandatory exit, market-driven exit, and mixed mechanisms. Choosing to consider geopolitical consistency and energy system similarity (such as Japan and Republic of Korea), development phase consistency (Vietnam and Indonesia), economic size and carbon emission weight (China and the United States), policy goal consistency but different policy tools (Germany and the United Kingdom), and advanced examples of VRE integration with complete withdrawal of coal-fired power (Denmark) for discussion.

3.5.1. Phase of Japan and Republic of Korea

In 2023, natural gas and coal accounted for 65% of Republic of Korea fuel mix, while the proportion of renewable energy was only 9.1%, still in phase 1 of renewable energy integration; Japan, on the other hand, has entered phase 2, with renewable energy accounting for 22.5% [53,54]. Coal-fired power provides electricity during this phase, ensuring the system's adequacy and the power grid's inertia. Republic of Korea and Japan have implemented measures such as establishing a carbon emission trading system and levying a carbon tax to promote emissions reduction and flexibility transformation of CFPPs. In addition to the energy consumption tax, Japan implemented a unique carbon tax in 2012. Republic of Korea has established an Emissions Trading System (ETS) but has not yet considered providing sufficient incentives to reduce coal-fired power generation significantly.

3.5.2. Phase of Vietnam and Indonesia

In 2023, fossil fuel power generation in Indonesia accounted for nearly 87% of electricity generation. Coal-fired power generation accounted for 61.8%, and renewable energy comprised 13%, in phase 1 of VRE integration [55]. Vietnam's coal-fired power contributes 46.8% to its electricity generation, with renewable energy making up 16%, and it is currently in phase 2 of renewable energy integration [56]. The CFPPs in both countries are still relatively young. Despite the rapid increase in VRE power generation, coal power remains the primary source that ensures the country's power supply [57]. Furthermore, legal frameworks for carbon pricing have been established. Indonesia issued Presidential Regulation No. 98 (2021) on carbon pricing in 2021 [58]. After a pilot emissions trading scheme involving 32 power plants in 2021, the ETS for CFPPs was launched in February 2023. Vietnam has an emissions trading scheme and an implicit carbon tax in the Environmental Protection Law of 2020 [59,60]. Vietnam's ETS plan will start a pilot phase from 2025 to 2027 before its official implementation in 2028 [61]. In response to these changes, Dang Hoang An, Chairman of Vietnam Electricity Group, has expressed a desire to enhance energy security and facilitate a green low-carbon transition, which includes promoting energy conservation and reduction in consumption, achieving ultra-low emissions, and flexibility transformation of CFPPs [62].

3.5.3. Phase of the United States and China

The United States has entered phase 2 with a renewable penetration rate of 21.3%. Despite announcing its withdrawal from the Paris Agreement in 2017, CO_2 emissions have steadily declined across all sectors, particularly in the power sector, over the past decade. The Department of Energy (DOE) published the Coal FIRST initiative, which emphasizes the development of modular, smaller, more efficient coal plants, characterized by near-zero emissions and enhanced flexibility, thus aligning with the evolving demands of the grid [63]. These types of CFPPs are also expected to be

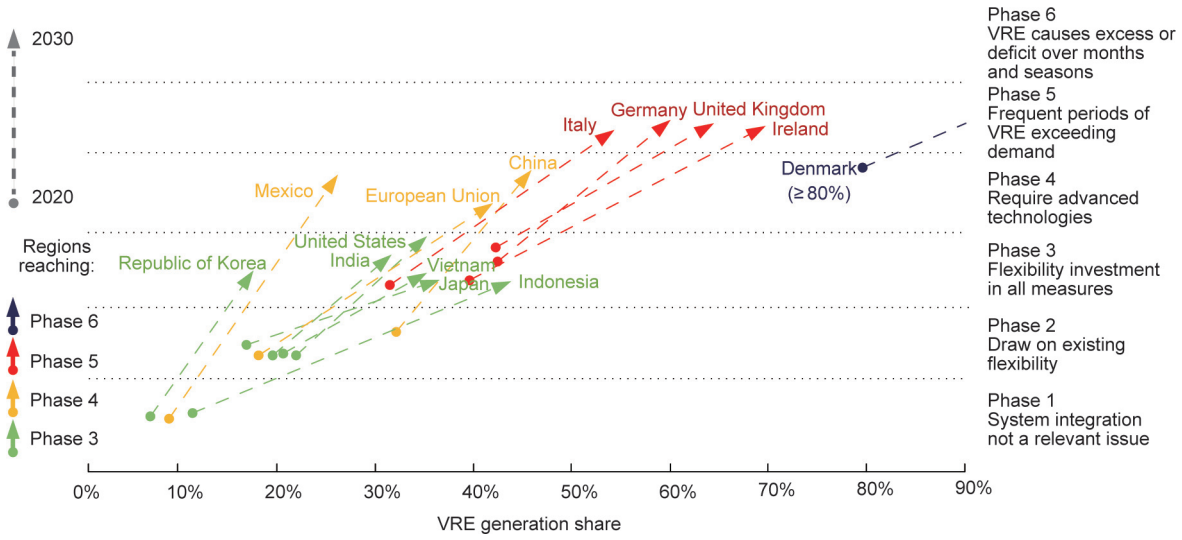

Fig. 3. Evolving flexibility needs in the decarbonized power system [31]. The division and description of different phases refer to Table 1.

Table 2
Policies related to different countries' power generation flexibility.

Ref.	Country	Publisher	Date	File name	Main related content
[33]	China	NEA	2016.6	Notice on the First Batch of Thermal Power Flexibility Transformation Pilot Projects (NEA (2016) No. 397)	To accelerate energy technology innovation, tap into the peak shaving potential of coal-fired units, and enhance the flexibility of China's thermal power operation, 16 projects, including Dandong Power Plant, have been identified as pilot projects for improving thermal power flexibility transformation
[34]	China	NDRC NEA	2016.7	Trial Measures for Priority Generation of Renewable Energy Peak Shaving Units (NEA (2016) No. 1558)	Proposing to establish an incentive mechanism for peak shaving units nationwide based on the principle of "whoever benefits from peak shaving" and encouraging power generation enterprises to carry out technological transformation of coal-fired power units
[35]	China	NDRC	2016.11	13th Five-Year Plan for Electric Power Development	One of the key tasks is to strengthen the construction of peak shaving capacity and improve system flexibility
[36]	China	NDRC NEA	2018.10	Clean Energy Consumption Action Plan (2018–2020) (NDRC Energy Regulations (2018) No. 1575)	Regarding thermal power flexibility transformation, it is proposed that relevant provincial government departments be responsible for formulating annual plans and linking the scale of thermal power flexibility transformation in each area to the total scale of new energy
[37]	China	NDRC NEA	2021.11	National Coal-fired Power Generating Unit Transformation and Upgrading Implementation Plan (NDRC (2021) No. 1519)	All newly built generating units realize flexible manufacturing, and the flexible transformation of existing generating units should be considered. This will deeply promote the clean, efficient, flexible, low-carbon, intelligent, and high-quality coal power development
[38]	China	NDRC NEA	2022.1	14th Five-Year Plan for Modern Energy System Planning	Fully implement the flexibility transformation of coal-fired power units, and prioritize enhancing the deep peak shaving capacity of 300 MW coal-fired power units
[39]	China	NDRC NEA	2024.7	Action Plan to Accelerate the Construction of A New Type of Power System (NDRC Energy Regulations (2024) No. 1128)	Focus on improving the design and equipment selection standard system of the new generation coal-fired power system, better adapting to the development requirements of the clean, low-carbon, flexible, and intelligent power system
[40]	United States	EPA	2015.8	Carbon Pollution Emission Guidelines for Existing Stationary Sources: Electric Utility Generating Units	The final rule greatly facilitates flexibility for electric generating units (EGUs) by establishing a basis for states to set trading-based emission standards and compliance strategies
[41]	United States	EPA	2018.8	Affordable Clean Energy (ACE) Rule	The EPA's latest rule offers states several options to cut emissions from power plants, though it recommends heat-rate efficiency improvements at existing coal power plants as the best choice
[42]	United States	DOE	2019.9	US DOE Invests $56 Million in Coal Technology Projects	The fourth funding opportunity award is for 5 million USD under DE-FOA-0002002, advanced materials for high-efficiency, flexible, and reliable coal-fueled power plants
[43]	Japan	Cabinet	2021.1	The Sixth Strategic Energy Plan	Reducing the carbon footprint of thermal power plants will remain a core element of the mix during the transitional period, improving safety, economic efficiency, and flexibility
[44]	Japan	Cabinet	2021.3	India–Japan Clean Energy Partnership	Carbon capture, utilization, and storage (CCUS)/carbon recycling
[45]	Republic of Korea	MOTIE	2019.1	Third Energy Master Plan	The plan also aimed to reduce the amount of power generation from coal by implementing environmental dispatch
[46]	Republic of Korea	MOTIE	2019.1	8th Basic Plan for Energy	While the basic directions emphasize reducing greenhouse gases and fine dust, specific measures for reducing coal power generation are insufficient
[47]	Denmark	DMCEU	2019.2	National Energy and Climate Plan	Developing markets for flexibility and ancillary services
[48]	Germany	BMWK	2016.7	Electricity Market Act	The act incorporates mechanisms to support flexible power plants, including coal plants, to help stabilize the grid as the share of VRE sources increases
[49]	Germany	BMWK	2020.9	Act to Reduce and End Coal-Fired Power Generation	Aiming at gradually reducing and eventually phasing out hard coal and lignite power generation. Its goal is to phase out coal in a socially responsible and economically viable manner
[50]	United Kingdom	DESNZ	2022.4	Energy Security Plan	The government has already identified and announced a site for the STEP power plant, which will be built in West Burton. This will transform the site of an existing coal power plant into a green energy cluster
[51]	Indonesia	MEMR	2021.10	The Electricity Supply Business Plan	To achieve the goal of renewable energy accounting for 23% of the power structure by 2025, as stipulated in the national power plan, it is considered to co-combust biomass in CFPPs
[52]	Vietnam	MIT	2022.12	Just Energy Transition Partnership	During the period of 2023–2030, developing micro-grids and flexible power sources

NEA: National Energy Administration; NDRC: National Development and Reform Commission; EPA: US Environmental Protection Agency; DOE: US Department of Energy; MOTIE: Ministry of Trade, Industry and Energy; DMCEU: Danish Ministry of Climate, Energy and Utilities; BMWK: German Federal Ministry for Economic Affairs and Climate Action; DESNZ: Department for Energy Security and Net Zero; MEMR: Ministry of Energy and Mineral Resources of Indonesia; MIT: Ministry of Industry and Trade.

beneficial for export to underdeveloped countries. With the increasing penetration of solar energy, the California Independent System Operator (CAISO) encounters a burgeoning challenge: Serving net peak demand while solar generation is unavailable. CAISO's flexible resources have fully transformed from coal to gas power, making significant progress towards phasing out coal-fired power [64]. In the PJM market, compensation is provided to coal power plants that offer grid regulation services, thereby incentivizing their flexibility upgrades. Coal-fired power accounted for 9.86% of the PJM fuel mix in March 2024, down from 23.8% in February 2022 [65].

China has entered phase 3 in renewable penetration, with 35.8% of its electricity supply from VRE and 58.5% from coal power in 2023. Although China possesses the world's largest installed renewable energy generation capacity, the issue of insufficient flexibility in the power grid remains severe, evidenced by the

significant power rationing and unstable supply problems that arose in 2021 [66]. Even in provinces with a high share of renewable energy, such as Qinghai (predominantly wind power), Sichuan, and Yunnan (mainly hydropower), coal serves a vital seasonal reserve role [67]. In Qinghai Province, which has achieved one month of 100% renewable supply, coal power plays a significant role as grid backup [68]. In Sichuan Province, with rich hydropower capacity, flexible coal power served as a pivotal means to maintain power system stability during the long summer drought season in 2022. China has undertaken large-scale and flexible transformations of its existing CFPPs and implemented a series of market and administrative measures to encourage flexible operation [69]. Concurrently, establishing and piloting the carbon emissions trading system will further promote the flexible transformation of coal-fired power, thereby providing robust support for the grid to absorb a higher proportion of new energy electricity [70].

3.5.4. Phase of Germany and the United Kingdom

As a global leader in renewable penetration, Germany has entered phase 4, with over 50% of annual electricity consumption derived from VRE, thanks to Germany's Energiewende since 2011 [71]. Currently, Germany's coal-fired power generation has evolved from its original design intention of efficient operation for basic and mid-loads to primarily undertaking the task of enhancing grid flexibility. Its research and application of coal-fired power flexibility technology are at the world's leading level. To ensure the stability and safety of the power grid, the German Energy Act has implemented an innovative strategy that utilizes the resources of soon-to-be-retired CFPPs to build a backup system explicitly designed for grid safety redundancy, commonly referred to as "coal-fired power backup" in the industry. This reserve system currently consists of eight generator units, with a total installed capacity of 2700 MW, accounting for about 6.14% of Germany's existing coal-fired power installed capacity [72]. This reflects a strategic consideration of balancing the efficient reuse of existing resources with the power grid's safety and stability in the energy transformation process.

The United Kingdom has also made significant progress in renewable energy and has entered phase 4 of deep integration. According to 2022 data, renewable energy generation accounts for 40% of annual electricity consumption, while the contribution from coal power generation has decreased to 3%. The United Kingdom plans to fully withdraw from coal power supply by 2025 at the latest [73,74]. To address the challenges related to the further increase in renewable energy's share, the United Kingdom is committed to enhancing the flexibility of coal-fired power units, including transforming combustion facilities that are suitable only for coal into those that also accommodate biomass fuels, reflecting the flexibility of CFPPs in fuel selection. Over the past five years, the United Kingdom has effectively promoted the energy structure transition from coal to natural gas by implementing a carbon price floor policy, establishing a foundation for a green and low-carbon energy transformation. Looking ahead, it is anticipated that by 2030, there will be greater demands on the energy system's integration capabilities. To this end, the United Kingdom is exploring and testing a range of solutions for flexible markets, including strengthening ties with the European energy market to enhance the security and resilience of energy supply. These measures aim to ensure the stable operation of the energy system and provide practical references for global energy transformation.

3.5.5. Phase of Denmark

Denmark has emerged as a pioneer in decarbonization. Additionally, it is at the forefront of developing flexible power systems. At the dawn of the new millennium, Denmark primarily relied on coal-fired power generation, supplemented by smaller gas-fired cogeneration plants. With VRE accounting for 81% of annual power consumption in 2023, Denmark has entered phase 5 of renewable integration [75]. In light of the European energy crisis in 2022, Denmark's policy emphasis has reaffirmed the critical necessity of diminishing reliance on fossil fuels and transitioning from coal to biomass energy supply. The share of coal decreased from 18% in 2011 to 6.9% in 2022. The transition from the primary supply to the backup power source plays the role of coal flexibility. The build of a Nordic electricity spot market, characterized by merit order dispatch and hourly pricing mechanisms, has been pivotal in motivating operators to enhance and capitalize on flexibility over the past two decades. The accommodation of VRE can be strengthened through high-level interconnections with robust markets of contiguous countries, proactive planning and forecasting, and a highly flexible coal fleet.

4. Metrics and retrofit options for coal power flexibility

4.1. Metrics

In power systems, numerous metrics quantify flexibility options, some of which are applicable to evaluate coal flexibility. The insufficient ramping resource expectation (IRRE) metric assesses the target frequency of instances where the power system cannot accommodate grid load needs over specific intervals, intuitively demonstrating the system's ability to cope with load fluctuations [76]. Both metrics quantify power system flexibility using Monte Carlo simulations and minimization programs. The Technical Uncertainty Scenarios Flexibility Index (T-USFI) concentrates on technical parameters to measure system adaptability. At the same time, the Technical Economic Uncertainty Scenarios Flexibility Index (TE-USFI) incorporates economic factors for cost–benefit evaluations. The selection between them hinges on the necessity of considering economic factors in power system planning [77]. Additionally, a parameter study is proposed to assess the role of providing medium-term flexibility. The offline metric evaluates the technical flexibility of generating units and the overall system [78]. The lack of ramp probability (LORP) metric examines a system's capability to meet anticipated variations in grid load and forecast errors using its generation resources, offering a practical evaluation of zonal ramp capability and helping system operators understand the flexibility of the entire region. The illustrated system and regional LORP metrics aim to enhance situational awareness, enabling real-time flexibility [79]. The composite flexibility metric (CFM) is calculated based on seven technical indexes of generating units, all used for unit commitment analysis [80], as shown in Table 3 [76–82].

Different coal power generation facilities have various characteristics of flexible resources. The main challenge in evaluating flexibility is quantifying the degree of system adequacy during the mobilization of flexible resources, reflecting their availability, and supporting the required characteristics of power plants. Fig. 4 summarizes the flexibility features of the quantitative techniques mentioned above and comprehensively illustrates which of these features are relevant.

4.2. Retrofit options

4.2.1. Global efforts and strategies

An action plan to enhance coal power flexibility in Germany includes numerous technical suggestions, many of which focus on the boiler-related components of the plants. These measures involve optimizing the combustion system and installing an indirect combustion system [83]. Danish power plants have optimized

Table 3
Flexibility evaluation metrics.

Ref.	Name	Scenario	Form	Type	Flexibility parameters considered
[76]	IRRE	Unit combination and economic dispatch	Algorithm	Economical	Ramp rate
[77]	T-USFI	Coal-fired power units and plants	Algorithm	Technical	Power capacity
[78]	TE-USFI	Coal-fired power units and plants	Algorithm	Technical & economical	Power capacity
[78]	Offline index	System flexibility and individual generators' flexibility	Comprehensive mathematical models	Technical	Ramp rate and power capacity
[79]	LORP	Ramp flexibility in multi-zonal power systems	Comprehensive mathematical models	Technical & economical	Ramp rate and power capacity
[80]	CFM	Power system and single generating unit	Comprehensive mathematical models	Technical	Ramp rate and power capacity
[81]	Flexibility chart	Unit combination and economic dispatch	Chart	Technical	Dispatchability and power capacity
[82]	FAST2 method	Unit combination and economic dispatch	Chart	Technical	Power capacity, multi-fuel capability, and cycling ability

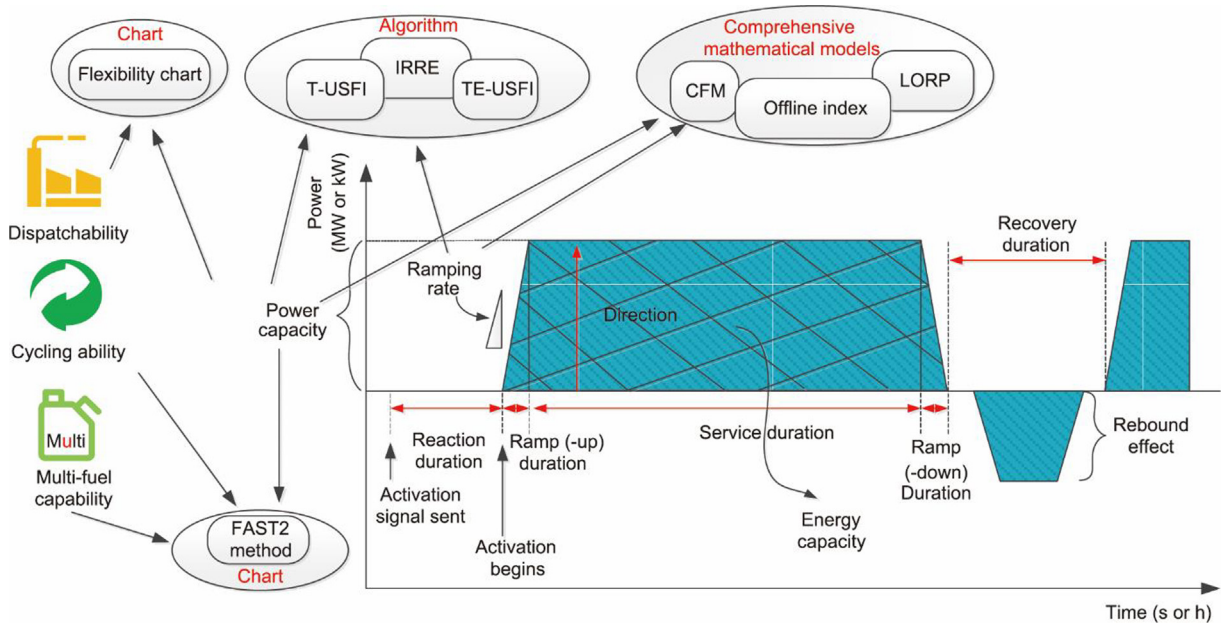

Fig. 4. Structural diagram of the coal-fired unit with flexibility options.

their flexibility for over two decades by concentrating on minimum loads and ramp rates. These improvements have been realized through investment in high-quality components and additional process control [84]. The United States has undertaken extensive physical upgrades to some CFPPs to mitigate and address the impacts of cycling and low-load operation, including design procedures for boiler ramp-up rates. Controlled ramp rates aid in minimizing thermal fatigue [85]. The flexibility index of certain coal-fired units has approached gas turbines, and their role has shifted from being an essential load power source to a flexible regulation power source [86]. India is exploring additional measures to facilitate the low-load operation of CFPPs, such as implementing appropriate flame detection systems, optimizing combustion processes, ensuring stable minimum mill operation, and using steam coil air preheaters [87]. Republic of Korea aims to lower the stable minimum load by retrofitting alternative boilers, while upgrading control systems and plant components can increase ramp rates, enabling the plants to operate at levels exceeding rated capacity within a short time frame [88].

The flexibility transformation of coal-fired power generation in China was initially piloted in the northeast region in 2016. Twenty-two coal-fired power projects were selected to initiate the promotion of flexibility transformation, but progress was slow [89]. In 2018, the National Energy Administration proposed prioritizing the enhancement of the deep peaking capacity of 300 MW coal-fired units [90]. In the first half of 2019, the release of policies related to the peak shaving auxiliary services market facilitated further transformation. In 2022, plans were established to implement a "triple transformation" for coal-fired generating units, which included energy-saving and consumption reduction, heating transformation, and flexibility transformation [91]. By that same year, efforts had accelerated to transform coal-fired power generation from the primary power source to providing reliable capacity, peak shaving, and frequency regulation as essential, and system-adjustable power sources [38,92].

4.2.2. Subsystem analysis

The entire coal-fired power generation process is highly complex, with the specific production flow illustrated in Fig. 5. It includes four typical production subsystems: boiler and fuel system, turbine system and coldend system, electrical systems, and control systems. A substantial amount of research supports the flexible transformation and upgrade of these subsystems, such as modification to ignition methods, upgrade of main component materials, optimization of control systems, and more, with the specific retrofit options detailed in Table 4.

When discussing different technological pathways to enhance coal power flexibility, we focus on two mainstream boiler unit

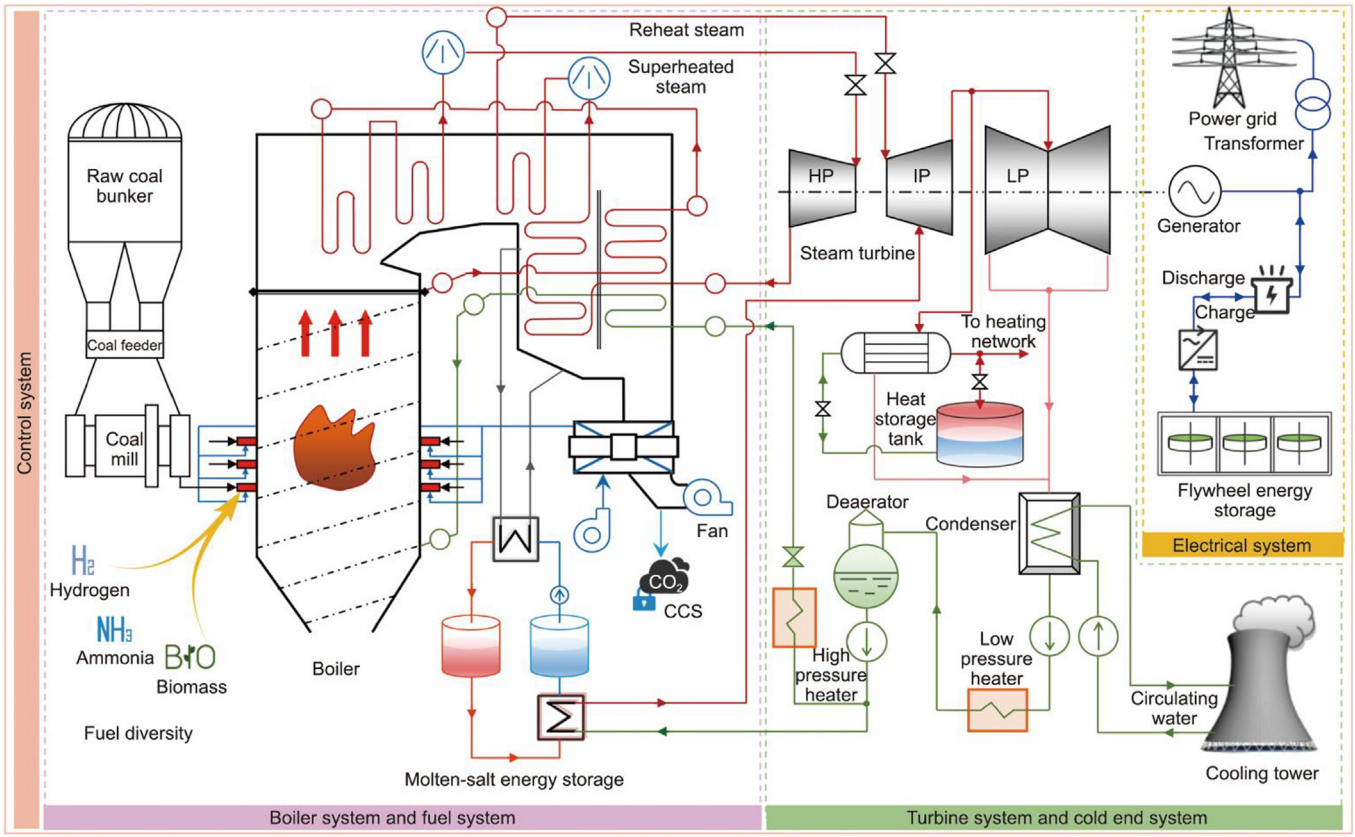

Fig. 5. Structural diagram of the coal-fired unit with flexibility options. HP: high pressure; IP: intermediate pressure; LP: low pressure.

Table 4
The impact on flexibility factors of retrofit options and limitations.

Subsystem	Option	Minimum load	Start-up time	Ramp rate	Limitations
Boiler system and fuel system	Switching mill operation mode and robust control of induction motors	✓	✓	–	Minimum output of the mill and mill switch reliability, grinding differential pressure
	Exploiting the storage capabilities of mills	–	–	✓	Response time and operational reliability
	Indirect firing	–	✓	✓	Coal drying and grinding, heat output
	Auxiliary firing ignition burner	✓	✓	✓	Fire stability and boiler design
	Thinner design of thick-walled components	–	✓	✓	High performance materials and cost
	Flue gas heat storage system	✓	–	✓	Material safety, boiler design and cost
	CCS	✓	–	–	Cost and efficiency
Turbine system and cold end system	Substitution of thick-walled components	–	✓	✓	High performance materials, cost and design standards
	Low pressure blade replacement	✓	–	–	Equipment reliability and replacement cost
	High pressure stage bypass	–	✓	✓	Performance and efficiency
	Condensate throttling regulation	–	–	✓	Operational safety and reliability, efficiency
	Steam heat storage system	✓	–	✓	Process design and efficiency, cost
Electrical system	Generator cooling technology	–	✓	✓	Thermal stress at generator windings
	Flywheel energy storage system	✓	–	✓	Structure design and cost
Control system	Optimized control system	✓	✓	✓	System structure and computability, controllability
	Condition monitoring and soft measurement	✓	✓	✓	Insufficient quantity and variety of monitoring equipment, cost
	Upgrade of factory engineering and control systems	✓	✓	✓	Structure design, reliability, performance, and cost
	Replacement of actuators	✓	✓	✓	Equipment reliability and cost

✓ represents the specific flexibility factors that this flexibility retrofit option can improve. We can observe that different flexibility modification options can enhance flexibility factors differently. Limitations are mainly influenced by factors such as materials, cost, and structural design.

designs: drum-type and once-through units [93]. Fig. 5 illustrates the structure of drum-type units, but we need to acknowledge the critical role of once-through units in power systems. Although drum-type units can withstand or reject higher load levels due to their structural characteristics, once-through units exhibit faster response rates to load variations. This difference means that once-through units may offer more flexible operational performance when quick responses to load changes are required. Therefore, when enhancing coal power flexibility, it is essential to consider not only the maximum load-bearing capacity of the units but also their response speed to load fluctuations. This is critical for ensuring the stability and efficient operation of the power system.

The rapid response characteristic of once-through units makes them a viable option, especially in the integration of renewable energy and in addressing grid fluctuations [94].

In addition, there are other sources to support them. Energy storage is an alternative auxiliary means of enhancing flexibility. It also provides a mechanism for storing energy generated during low demand or high supply and utilizing it during periods of high demand [95]. Significant advancements in storage technology and the ongoing reduction in capital costs make it feasible to provide flexibility during this critical period, with options such as thermal storage tanks, flywheels, and molten salt. This mitigates and even eliminates the need for coal power peak shaving, thereby augmenting flexibility. Equally importantly, fuel flexibility is also a practical option, like co-firing with biomass, hydrogen, and ammonia. CCS technology can increase standby capacity (accounting for 10%–20% of the installed capacity of coal power plants) by reducing carbon capture load during peak electricity consumption periods and improving carbon capture load during off-peak periods, thereby increasing standby capacity by 20% [96]. We also specifically illustrate the connection measures of these retrofit options with the coal-fired power units in Fig. 5.

4.2.3. Classification of decarbonization

Decarbonization of coal-fired units can be classified into two main approaches: energy efficiency improvements and CCS technologies [97,98]. Energy efficiency improvements focus on optimizing the efficiency of coal units to reduce fuel consumption and carbon emissions. This can be achieved through upgrading equipment, improving boiler technology, optimizing heat recovery, and enhancing combustion efficiency [99]. On the other hand, CCS technology directly captures carbon dioxide produced during coal combustion and stores it underground, preventing it from entering the atmosphere and thereby mitigating greenhouse gas emissions. Combining both methods can help coal power generation achieve a near-zero emission target [100]. However, combining these two methods presents challenges. While energy efficiency improvements can reduce energy consumption, the potential for further gains is limited and requires substantial investment and technological development. CCS technology still faces challenges such as insufficient technological maturity, high costs, and limited storage capacity. Combining energy efficiency improvements and CCS remains viable for achieving near-zero emissions from coal units, especially during the transitional period when renewable energy cannot fully replace coal power [101]. With continued technological innovation and policy support, these technologies' efficiency and economic viability are expected to improve, further advancing the decarbonization process in the coal power industry.

5. Flexibility costs and benefits

5.1. Retrofit operation maintenance cost

The technical feasibility of achieving flexibility in CFPPs has been demonstrated, and various flexibility retrofit solutions are available to address different application requirements [102]. From an economic perspective, transforming traditional CFPPs into efficient and flexible power generation units requires significant one-time capital investment for technological upgrades and long-term costs associated with flexible operation. Regarding the operational cost structure, the cost composition of power generation becomes more diversified after flexibility retrofits [103,104]. This primarily includes the higher coal consumption costs to enhance flexibility, additional expenses from raised emissions under stricter carbon emission regulations, and capital investment for the ongoing operation of CCS systems. Notably, long-term operation of the units at low loads and frequent cycling operations in response to grid demands exacerbate wear and tear on components and thermal stress loads. Directly increasing the failure rates and economic burden of maintenance [105].

Further analysis of the cost composition of CFPPs during peak shaving reveals that it includes the direct costs of coal procurement and usage, additional maintenance costs due to accelerated equipment wear, costs associated with using special fuels for peak shaving, environmental compliance costs from emissions management (such as pollution tax payments and ash disposal), and implied economic costs associated with lost power due to efficiency fluctuations during peak shaving [106]. In short, the financial consideration of coal-fired power flexibility is a complex and multidimensional issue that requires a comprehensive evaluation of the long-term benefits of technological upgrades and the dynamic costs incurred in the short term.

5.2. Capital expenditure (CAPEX) and fixed cost

The impact of enhancing coal power flexibility on costs primarily manifests through CAPEX, which is necessary at the plant level to implement various interventions to accommodate flexible operation demands [107]. The CAPEX for the flexible activation process of coal-fired units includes depreciation, labor, repair, and financial costs. These costs depend on the required modifications and operational costs associated with decreased performance, increased maintenance, and a shortened lifespan. The service life cost escalates due to the rapid deep peak shaving process, where frequent changes in output induce low-cycle fatigue and creep loss. Additionally, there is an augmented expenditure on water, chemicals, labor, and other ancillary activities. The heightened likelihood of noncompliance with grid regulations can also result in financial losses. The CAPEX encompasses the initial capital outlay for baseload plants and additional CAPEX for converting them into flexible plants. The CAPEX incurred in retrofitting investments and fostering greater flexibility in coal power plants results in reduced investment in coal heat-only boilers, which typically have lower capital costs [108]. We focus on the cost of implementing technological flexibility. In the flexibility cost, we have also summarized the attention levels that various countries pay to different types of expenses. Together with the subsequent flexibility benefits, we have assessed their overall attention, as shown in Tables 5 and 6 [14,106,109–113].

5.3. Flexibility benefits

The economic benefits of coal power flexibility play a crucial role in investment decisions and are closely linked to carbon, energy, and ancillary service prices. Flexibility retrofits can alter the proportion structure of electricity output and auxiliary services in operators' income sources, allowing them to benefit from the carbon trading market, grid auxiliary services, and emission reduction subsidies. Table 7 [114–117] summarizes the different benefits and evaluation methods for the flexibility transformation of coal-fired power generation.

European countries rarely offer policy subsidies for the flexibility retrofit of CFPPs. Instead, they mainly depend on price signals from the spot market at different periods to guide market participants in adjusting their output during peak and off-peak hours to capture flexibility benefits. Other services, such as frequency regulation, automatic generation control (AGC), voltage and reactive power control, system reserve, and black start, are traded in ancillary service markets. International experience shows that the spot electricity market, composed of day-ahead and intraday markets, is the most effective mechanism for enhancing system operational

Table 5
Costs and benefits of attention level of coal power flexibility in different regions.

Region	Attention	Cost				Benefit			
		Life loss	ENV	Fuel	Peak shaving	CCS	Ancillary services	ETS	Subsidy
Denmark	High	●	●	●	●	●	●	●	○
Germany	High	◐	●	●	●	●	●	●	○
European Union	Medium	◐	●	●	◐	◐	●	●	◐
United States	Medium	●	◐	●	◐	◐	●	●	◐
Japan	Medium	◐	●	●	◐	◐	◐	●	●
China	Medium	◐	◐	●	●	◐	◐	●	●
Republic of Korea	Medium	◐	◐	●	◐	◐	◐	●	●
India	Low	◐	○	◐	◐	◐	○	◐	●

● represents currently high attention, ◐ represents currently medium attention, ○ represents low attention. These regions exist in Fig. 3. We collect five reports about the coal power flexibility for each country. If the keywords mentioned in the reports are 1 and not mentioned, they are considered 0. Among the five reports, a total of 0–1 are mentioned as low attention, 2–4 as medium attention, and five as high attention. ENV: environment.

Table 6
Paradigm for quantifying the cost of coal power flexibility.

Item	Refs.	Quantization function
Life loss cost	[106,109]	$A(P_{i,t}) = \frac{1}{2N_f(P_{i,t})} \cdot \delta S_u$
ENV cost	[106,110]	$E^{q}_{i,t} = \varepsilon_i P_{i,t} \Delta t$ $E^{a}_{i,t} = \sigma_i P_{i,t} \Delta t$ $C^{carbon}_{i,t} = \mu\left(E^{a}_{i,t} - E^{q}_{i,t}\right)$
Fuel cost	[14,111]	$C^{coal}_{i,t} = (aP^2_{i,t} + bP_{i,t} + c) \cdot S_{coal}$ $C^{oil}_{i,t} = Q^{oil}_{i,t} S_{oil}$
Peak shaving cost	[112,113]	$F = f_{mh} + f_{qt} = \sum_{t=1}^{N_T} \sum_{i=1}^{N_G} a_i P^2_{i,t} + b_i P_{i,t} + c_i + \sum_{t=1}^{N_T} \sum_{i=1}^{N_G} S_{it} u_{it} (1 - u_{i(t-1)})$

Symbolic variables and their units can be found in Table S1 in Appendix A.

Table 7
Paradigm for quantifying the benefits of coal power flexibility.

Items	Ref.	Objective functions	Application	Limitations
CCS	[114]	$Benefit_{D,i,y} = (E_{Historical,y} - E_{i,y}) \times CP$	Mature carbon market mechanisms and predictable carbon prices	Assuming long-term stability of carbon prices and ignoring market fluctuation risks
Auxiliary service	[115]	$F_{e,pro} = \eta_e \int_0^{t_1} P_{D,e,t} C_{pr,e,t}\, dt - \int_0^{t_2} P_{C,e,t} C_{pr,e,t}\, dt$	Scenario of separate pricing for auxiliary services in market-oriented power systems	Ignoring price fluctuations in medium and long-term capacity auctions
ETS	[116]	$EM_{i,t} = \theta_{coal} \cdot D_{i,t,coal} + \theta_{oil} \cdot D_{i,t,oil} + \theta_{gas} \cdot D_{i,t,gas}$ $T_{CO_2 t} = (1 - tcer_t)_{CO_2} ref_t$ $T_{CO_2 t} = \sum_t EM_{i,t}$ $C_{i,t} = P_{CO_2 i,t} \cdot EM_{i,t}$ $\sum_i C_{i,t} = GYETS_t$	Short-term profit forecasting requires transparent carbon prices and clear quota allocation rules	Not considering the transaction premium caused by insufficient liquidity in the carbon market
Subsidy	[117]	$F_G = \int_0^{t_3} \sum_{i=1}^{n} \{C_{pr,GP}[P_{a,i} - P_{G,i}(t)]\} dt$	High demand for peak shaving in the power system and clear subsidy rules from the market	Sensitivity to prediction errors in peak shaving demand of the power grid

Symbolic variables and their units can be found in Table S1 in Appendix A.

flexibility and facilitating the integration of renewable energy sources.

Prices in the spot market fluctuate based on supply and demand dynamics, effectively guiding the release of flexibility potential in CFPPs. For instance, Denmark and Germany's grid integration guidelines specify the essential peak-shaving capacity for coal-fired plants (with values similar to those in China) [118,119]. Still, under market price signals, coal plants have proactively implemented flexibility retrofits, with peak-shaving capacities exceeding the ranges specified by the grid integration guidelines.

In northeast China, when the average load factor of CFPPs drops below the benchmark for compensated peak shaving, power generation companies can obtain peak-shaving compensation through real-time deep peak-shaving transactions. They can implement a tiered pricing method to provide two-tier floating price quotes during different periods: The first tier of peak shaving is between 40% and 50%, with a price ceiling of 0.4 CNY·(kW·h)$^{-1}$; the second tier, below 40%, ranges from 0.4 to 1.0 CNY·(kW·h)$^{-1}$ [120].

In north China, the Shandong grid's compensated peak shaving employs a tiered pricing model, where power generation companies provide tiered floating price quotations at different periods. The first tier (60% < load factor < 70%, gradually decreasing by 10%) for the minimum sustained output for bottomless peak shaving requires continuous incremental price quotations. Meanwhile, output below this minimum sustained output for bottomless peak shaving can be separately quoted for shutdown peak shaving. The compensated peak-shaving clearing price has an upper limit, with output reduction peak shaving temporarily priced at 150 CNY·(MW·h)$^{-1}$ and shutdown peak shaving priced at 400 CNY·(MW·h)$^{-1}$ [121].

In east China, the power plants in these areas (East China Grid Dispatch, Shanghai, Jiangsu, Zhejiang, Anhui, and Fujian Provinces) have basic peak shaving ranges of 43%, 54%, 41%, 51%, 50%, and 47% of their rated capacities, respectively. This means the output adjustment ranges for the plants are between 57%–100%, 47%–100%, 59%–100%, 49%–100%, 50%–100%, and 53%–100% of their

rated capacities. During load valleys or peak-shaving difficulty periods, conventional coal-fired plants (or plant combinations) whose output falls below the basic peak-shaving lower limit (calculated by the total capacity ratio of the plant or combination) will receive compensation for the under-generation. The compensation standards are as follows: 20 CNY·(MW·h)$^{-1}$ for a load factor between 50% and 60%; 40 CNY·(MW·h)$^{-1}$ for a load factor between 40% and 50%; 80 CNY·(MW·h)$^{-1}$ for a load factor between 30% and 40%; and 160 CNY·(MW·h)$^{-1}$ for a load factor below 30% [122].

In southern China, compensated peak shaving is divided into bottomless and start–stop peak shaving. Deep peak shaving refers to operations when the plant's active output is below 50% of its rated capacity. Start-stop peak shaving refers to a method where grid conditions require a coal-fired plant to shut down and restart within 24 hours. The compensation standards for start–stop peak shaving are 25 000 CNY per 10 000 kW in Guangdong, 20 000 CNY·(10 MW)$^{-1}$ in Guangxi, Yunnan, and Hainan, and 25 000 CNY·(10 MW)$^{-1}$ in Guizhou. For coal-fired plants with deep peak-shaving output between 40%–50% of their rated capacity, the compensation standard is three times the deep peak-shaving compensation; for output below 40%, the standard is six times the deep peak-shaving compensation, with rates of 60 CNY·(MW·h)$^{-1}$ in Guangdong, 30 CNY·(MW·h)$^{-1}$ in Guangxi, 24 CNY·(MW·h)$^{-1}$ in Yunnan, 18 CNY·(MW·h)$^{-1}$ in Guizhou, and 45 CNY·(MW·h)$^{-1}$ in Hainan [123].

6. Discussion: Establishing the proper value orientation for coal flexibility

6.1. Coal power flexibility and energy security

Globally, energy security is a critical component of national strategy. For many countries reliant on coal power generation, flexible coal power is vital in ensuring electricity stability. In response to rapidly growing demand, flexibility retrofitting allows CFPPs to quickly adjust to load fluctuations, preventing economic losses and social unrest that may arise from power shortages. This is particularly crucial in Asia, where many CFPPs are relatively new, and their infrastructure investments have not yet been fully recouped. Phasing out coal power prematurely without adequate preparation could lead to significant political, economic, and social costs. Implementing a flexible coal-fired power generation strategy requires a systematic approach for developing countries that rely on coal as a primary energy source. Establishing a robust policy framework is vital. These countries can create incentive policies, such as tax reductions and technology subsidies, to support flexibility retrofits. For instance, developing nations could offer tax incentives and low-interest loans to encourage power plants to upgrade for flexibility. On the technical side, advanced international technologies can be introduced while improving training for local technical personnel. Collaboration with global energy companies could bring state-of-the-art retrofitting technologies to enhance plant operational efficiency.

6.2. Applicability during the energy transition period

Flexible coal-fired power generation can reduce energy investment, ensure energy equity, and secure power supply in developing countries. By improving flexibility in coal power, developing countries can fulfill their climate change commitments required by the international community while continuing their economic development. Such policies help establish a fairer energy landscape, ensuring that developing countries can still exercise the right to economic development while minimizing the socioeconomic costs of a rapid energy transition. Access to clean energy is indispensable for fostering sustainable human development. Consequently, we have both a responsibility and an opportunity to achieve the global goal of eradicating energy poverty by 2030. However, these urgent emission abatement policies may unintentionally worsen energy poverty. Coal-fired power generation is experiencing significant growth in Asia, primarily in China, India, Indonesia, and Vietnam [124]. In these regions, which are highly reliant on coal, resistance to the phasing out of coal power generation can manifest at various levels. Transforming legacy CFPPs through flexibility retrofits ensures a socially equitable transition toward decarbonized development in these countries.

6.3. Future research directions

Despite the potential advantages of flexible CFPPs in the energy transition, numerous unresolved research challenges remain. From a technical perspective, further exploration is necessary to enhance coal power plants' response speed and operational efficiency through equipment upgrades like high-efficiency combustion technologies and advanced control systems, all while minimizing environmental impacts. Research into novel materials and coating technologies is critical for improving the durability and reliability of equipment subjected to frequent start–stop cycles and rapid load variations, reducing thermal stress and mechanical fatigue damage. In the economic sphere, research should ensure flexible operations' financial sustainability. This involves exploring pricing mechanisms or subsidy policies to offset the increased costs due to frequent startups, shutdowns, and low-load operations. Policy-related research is equally vital, focusing on the design of suitable market mechanisms and policies to encourage the transition of conventional CFPPs to flexible operational models. Key areas of concentration include the development of carbon market mechanisms, capacity markets, and ancillary service markets.

7. Conclusions and outlook

Although coal-fired power generation is a significant source of carbon dioxide emissions, it remains essential in the energy transition. CFPPs can adjust to the fluctuations of renewable energy in the power system through flexibility retrofits, offering reliable backup and regulation capabilities. Naturally, optimizing manufacturing processes, operational procedures, and the physical and structural design of key equipment is crucial for advancing flexibility technologies toward more mature and efficient stages of development. At the same time, the innovation and application of related technologies are pivotal: For instance, the maturation and deployment of energy storage technologies provide more substantial flexibility support for CFPPs, while the development of CCS technologies can further reduce carbon emissions from coal-fired power generation, presenting solutions for achieving low-carbon targets.

Existing practices demonstrate that policy support significantly enhances countries' willingness to engage in flexibility retrofits for CFPPs. Due to the diversity of technological approaches, the policy measures adopted by different countries to promote flexible operations in coal-fired plants vary. Governments should set clear and practical objectives to guide the enhancement of coal power flexibility while standardizing improvement measures to ensure their effectiveness. These standardized measures must undergo multidimensional evaluation to assess their impacts on flexible generation performance, plant lifespan, and cost variations under diverse boundary conditions.

In the new development phase, research on coal-fired power flexibility should go beyond traditional definitions and integrate cross-disciplinary approaches, particularly those considering

various scenarios, policies, costs, and market mechanisms. These approaches aim to address the intersection of flexible generation and market behavior, fostering interdisciplinary collaboration. The extent of adjustments in coal-fired power generation varies significantly across countries, primarily due to differences in local resource endowments, coal's current share in the energy mix, economic structures, and labor markets. Promoting the transformation of coal-fired power generation should be based on fair development rights, necessitating comprehensive participation from all stakeholders and full consideration of its impacts on energy security and socio-economic development.

CRediT authorship contribution statement

Jinze Li: Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation. **Fang Fang:** Writing – review & editing, Writing – original draft, Supervision, Resources, Methodology, Funding acquisition, Formal analysis, Conceptualization. **Yuanye Chen:** Writing – original draft, Investigation, Formal analysis, Data curation. **Songyuan Yu:** Writing – original draft, Methodology, Investigation, Formal analysis. **Jizhen Liu:** Writing – review & editing, Supervision, Methodology, Formal analysis, Conceptualization. **Yanjun Du:** Validation, Methodology, Formal analysis, Data curation. **Ming Du:** Resources, Methodology, Investigation, Formal analysis. **Yi Zhang:** Software, Methodology, Investigation, Formal analysis. **Qinghua Wang:** Validation, Resources, Methodology, Formal analysis. **Yuguang Niu:** Resources, Investigation, Formal analysis.

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.

Acknowledgments

This work was supported by the National Key Research and Development Project of China (2022YFB4100400). This work was supported by the Beijing Huairou Laboratory, and the authors are grateful to the Huairou Laboratory for the concept discussion from a technical perspective.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.eng.2025.06.019.

References

[1] Welsby D, Price J, Pye S, Ekins P. Unextractable fossil fuels in a 1.5 °C world. Nature 2021;597:230–4.
[2] Keyßer LT, Lenzen M. 1.5 °C degrowth scenarios suggest the need for new mitigation pathways. Nat Commun 2021;12:2676.
[3] Glanemann N, Willner SN, Levermann A. Paris climate agreement passes the cost–benefit test. Nat Commun 2020;11:110.
[4] Achakulwisut P, Erickson P, Guivarch C, Schaeffer R, Brutschin E, Pye S. Global fossil fuel reduction pathways under different climate mitigation strategies and ambitions. Nat Commun 2023;14:5425.
[5] Masson-Delmotte V, Zhai P, Pörtner HO, Roberts D, Skea J, Shukla PR, et al. Global warming of 1.5 °C. Report. Geneva: World Meteorological Organization; 2019.
[6] Jewell J, Vinichenko V, Nacke L, Cherp A. Prospects for powering past coal. Nat Clim Chang 2019;9:592–7.
[7] COP28 agreement signals beginning of the end of the fossil fuel era [Internet]. Bonn: United Nations Framework Convention on Climate Change; 2023 Dec 13 [cited 2024 Oct 6]. Available from: https://unfccc.int/news/cop28-agreement-signals-beginning-of-the-end-of-the-fossil-fuel-era.
[8] Ruhnau O, Stiewe C, Muessel J, Hirth L. Natural gas savings in Germany during the 2022 energy crisis. Nat Energy 2023;8:621–8.
[9] Global coal demand set to remain at record levels in 2023 [Internet]. Paris: International Energy Agency; 2023 Jul 27 [cited 2024 Oct 6]. Available from: https://www.iea.org/news/global-coal-demand-set-to-remain-at-record-levels-in-2023.
[10] Muttitt G, Price J, Pye S, Welsby D. Socio-political feasibility of coal power phase-out and its role in mitigation pathways. Nat Clim Chang 2023;13:140–7.
[11] Kalkuhl M, Steckel JC, Montrone L, Jakob M, Peters J, Edenhofer O. Successful coal phase-out requires new models of development. Nat Energy 2019;4:897–900.
[12] World energy balances 2019: summary energy balances. Report. Paris: International Energy Agency; 2019.
[13] Heptonstall PJ, Gross RJ. A systematic review of the costs and impacts of integrating variable renewables into power grids. Nat Energy 2021;6:72–83.
[14] Shi Y, Li Y, Zhou Y, Xu R, Feng D, Yan Z, et al. Optimal scheduling for power system peak load regulation considering short-time startup and shutdown operations of thermal power unit. Int J Elec Power 2021;131:107012.
[15] Gonzalez-Salazar MA, Kirsten T, Prchlik L. Review of the operational flexibility and emissions of gas- and coal-fired power plants in a future with growing renewables. Renew Sustain Energy Rev 2018;82:1497–513.
[16] Jenkins JD, Zhou Z, Ponciroli R, Vilim RB, Ganda F, de Sisternes F, et al. The benefits of nuclear flexibility in power system operations with renewable energy. Appl Energy 2018;222:872–84.
[17] Liu L, Guo H, Dai L, Liu M, Xiao Y, Cong T, et al. The role of nuclear energy in the carbon neutrality goal. Prog Nucl Energy 2023;162:104772.
[18] Firdaus N, Mori A. Stranded assets and sustainable energy transition: a systematic and critical review of incumbents' response. Energy Sustain Dev 2023;73:76–86.
[19] Song F, Mehedi H, Liang C, Meng J, Chen Z, Shi F. Review of transition paths for coal-fired power plants. Global Energy Interconnect 2021;4:354–70.
[20] Flexibility in thermal power plants with a focus on existing coal-fired power plants. Report. Berlin: Agora Energiewende; 2017.
[21] Flexibility in conventional power plants: innovation landscape brief. Report. Abu Dhabi: International Renewable Energy Agency; 2020.
[22] Status of power system transformation 2018. Report. Paris: International Energy Agency/Organisation for Economic Co-operation and Development; 2018.
[23] Cherp A, Vinichenko V, Tosun J, Gordon JA, Jewell J. National growth dynamics of wind and solar power compared to the growth required for global climate targets. Nat Energy 2021;6:742–54.
[24] Liu Z, Wang C, Fan J, Liu M, Xing Y, Yan J. Enhancing the flexibility and stability of coal-fired power plants by optimizing control schemes of throttling high-pressure extraction steam. Energy 2024;288:129756.
[25] Kirkegaard JK, Rudolph DP, Nyborg S, Solman H, Gill E, Cronin T, et al. Tackling grand challenges in wind energy through a socio-technical perspective. Nat Energy 2023;8:655–64.
[26] Zame KK, Brehm CA, Nitica AT, Richard CL, Schweitzer III GD. Smart grid and energy storage: policy recommendations. Renew Sustain Energy Rev 2018;82:1646–54.
[27] Denholm P, Arent DJ, Baldwin SF, Bilello DE, Brinkman GL, Cochran JM, et al. The challenges of achieving a 100% renewable electricity system in the United States. Joule 2021;5:1331–52.
[28] China energy outlook: understanding China's energy and emissions trends. Report. Berkeley: China Energy Group; 2020.
[29] World energy outlook 2022. Report. Paris: International Energy Agency; 2022.
[30] China 2050 high renewable energy penetration scenario and roadmap study. Report. Beijing: Energy Research Institute; 2015. Chinese.
[31] World energy outlook 2025. Report. Paris: International Energy Agency; 2025.
[32] Denholm P, Hand M. Grid flexibility and storage required to achieve very high penetration of variable renewable electricity. Energy Policy 2011;39:1817–30.
[33] Notice on the first batch of thermal power flexibility transformation pilot projects. Report. Beijing: National Energy Administration of China; 2016. Chinese.
[34] Trial measures for priority generation of renewable energy peak shaving unit. Report. Beijing: National Energy Administration of China; 2016. Chinese.
[35] Thirdth five-year plan for electric power development. Report. Beijing: National Energy Administration of China; National Development and Reform Commission of China; 2016. Chinese.
[36] Clean energy consumption action plan (2018–2020). Report. Beijing: National Energy Administration of China; National Development and Reform Commission of China; 2018. Chinese.
[37] National coal-fired power generating unit transformation and upgrading implementation plan. Report. Beijing: National Energy Administration of China; National Development and Reform Commission of China; 2021. Chinese.
[38] Fourth five-year plan for electric power development. Report. Beijing: National Energy Administration of China; National Development and Reform Commission of China; 2022. Chinese.
[39] Action plan to accelerate the construction of a new type of power system. Report. Beijing: National Energy Administration of China; National Development and Reform Commission of China; 2024. Chinese.

[40] Carbon pollution emission guidelines for existing stationary sources: electric utility generating units. Report. Washington, DC: United States Environmental Protection Agency; 2024.
[41] Affordable clean energy rule. Report. Washington, DC: United States Environmental Protection Agency; 2018.
[42] Department of energy invests $56 million in coal technology projects. Report. Washington, DC: US Department of Energy; 2019.
[43] The sixth strategic energy plan. Report. Tokyo: Ministry of the Environment Government of Japan; 2021. Japanese.
[44] India–Japan clean energy partnership. Report. Tokyo: Ministry of the Environment Government of Japan; 2021. Japanese.
[45] Third energy master plan. Report. Sejong: Ministry of Trade, Industry and Energy of Korea; 2019. Korean.
[46] Eighth basic plan for energy. Report. Sejong: Ministry of Trade, Industry and Energy of Korea; 2019. Korean.
[47] Energy & industrial strategy of United Kingdom, national energy and climate plan. Report. London: UK Department for Business and Trade; 2019.
[48] The energy act. Report. Bonn: Deutsche Bundesnetzagentur; 2019. German.
[49] Act to reduce and end coal-fired power generation. Report. Bonn: Deutsche Bundesnetzagentur; 2019. German.
[50] Energy security plan. Report. Copenhagen: Danish Energy Agency; 2022. Danish.
[51] Joint statement by the government of the republic of Indonesia and international partners group members on the Indonesia just energy transition plan. Report. Brussels: European Commission; 2022.
[52] Political declaration on establishing the just energy transition partnership with Vietnam. Report. Brussels: European Commission; 2022.
[53] Energy system of Korea, 2024. Report. Paris: International Energy Agency; 2024.
[54] Energy system of Japan, 2024. Report. Paris: International Energy Agency; 2024.
[55] Rangelova K, Setyawati D. Indonesia and the Philippines coal dependency surges past China and Poland. Report. London: Ember; 2024.
[56] Power sector overview. Report. London: Ember; 2024.
[57] Do TN, Burke PJ, Nguyen HN, Overland I, Suryadi B, Swandaru A, et al. Vietnam's solar and wind power success: policy implications for the other Asian countries. Energy Sustain Dev 2021;65:1–11.
[58] Do TN, Burke PJ. Phasing out coal power in two major southeast Asian thermal coal economies: Indonesia and Vietnam. Energy Sustain Dev 2024;80:101451.
[59] Do TN, Burke PJ, Baldwin KG, Nguyen CT. Underlying drivers and barriers for solar photovoltaics diffusion: the case of Vietnam. Energy Policy 2020;144:111561.
[60] Ordonez JA, Vandyck T, Keramidas K, Garaffa R, Weitzel M. Just energy transition partnerships and the future of coal. Nat Clim Chang 2024;14:1026–9.
[61] Do TN, Burke PJ. Phasing out coal power in a developing country context: insights from Vietnam. Energy Policy 2023;176:113512.
[62] [Jiang Yi holds talks with Dang Hoang An, chairman of Vietnam Power Group]. Report. Beijing: China Huadian Corporation LTD; 2023. Chinese.
[63] Energy policies of IEA countries: United States 2019 review. Report. Paris: International Energy Agency; 2019.
[64] Competitive electricity markets spotlight: California ISO. Report. New York: Electric Power Supply Association; 2021.
[65] pjm.com [Internet]. Valley Forge: PJM Interconnection; c2025 [cited 2024 Oct 6]. Available from: https://www.pjm.com/.
[66] [The National Energy Administration organized an analysis meeting on the development and construction situation of renewable energy in China in February 2023]. Beijing: National Energy Administration of China; 2023. Chinese.
[67] He G, Lin J, Sifuentes F, Liu X, Abhyankar N, Phadke A. Rapid cost decrease of renewables and storage accelerates the decarbonization of China's power system. Nat Commun 2020;11:2486.
[68] [Clean energy makes Qinghai more beautiful]. Report. Xining: The People's Government of Qinghai Province; 2023. Chinese.
[69] Eight aspects of the "13th Five-Year Plan for Electric Power Development" draw a blueprint for electric power development. Report. Beijing: National Energy Administration of China; 2016. Chinese.
[70] Duan WL, Qi M, Designing S. China's national carbon emissions trading system in a transitional period. Clim Policy 2018;18:1–6.
[71] Rückblick 2023: Erneuerbare schafften die 50-prozent-marke. Report. Munich: BMWK; 2024.
[72] Germany 2020 energy policy review. Report. Paris: International Energy Agency; 2020.
[73] Energy system of United Kingdom. Report. Paris: International Energy Agency; 2022.
[74] Energy policies of IEA countries: United Kingdom 2019 review. Report. Paris: International Energy Agency; 2019.
[75] Denmark 2023 energy policy review. Report. Paris: International Energy Agency; 2023.
[76] Lannoye E, Flynn D, O'Malley M. Evaluation of power system flexibility. IEEE Trans Power Syst 2012;27:922–31.
[77] Capasso A, Falvo MC, Lamedica R, Lauria S, Scalcino S. A new methodology for power systems flexibility evaluation. In: Proceedings of 2005 IEEE Russia Power Tech; 2005 Jun 27–30; St. Petersburg, Russia. IEEE; 2005.
[78] Ma J, Silva V, Belhomme R, Kirschen DS, Ochoa LF. Evaluating and planning flexibility in sustainable power systems. In: Proceedings of 2013 IEEE Power & Energy Society General Meeting; 2013 Jul 21–25; Vancouver, BC, Canada. IEEE; 2013. p. 1–11.
[79] Thatte AA, Xie L. A metric and market construct of inter-temporal flexibility in time-coupled economic dispatch. IEEE Trans Power Syst 2015;31:3437–46.
[80] Oree V, Hassen SZS. A composite metric for assessing flexibility available in conventional generators of power systems. Appl Energy 2016;177:683–91.
[81] Yasuda Y, Carlini EM, Estanqueiro A, Eriksen PB, Flynn D, Herre LF, et al. Flexibility chart 2.0: an accessible visual tool to evaluate flexibility resources in power systems. Renew Sustain Energy Rev 2023;174:113116.
[82] The power of transformation: wind, sun and the economics of flexible power systems. Report. Paris: International Energy Agency; 2014.
[83] Henderson C. Increasing the flexibility of coal-fired power plants. Report. London: IEA Clean Coal Centre; 2014.
[84] Flexibility in the power system Danish and European experiences. Report. Copenhagen: Danish Energy Agency; 2015.
[85] Flexible coal: evolution from baseload to peaking plant. Report. Golden: National Renewable Energy Lab; 2013.
[86] Tampubolon AP, Tumiwa F, Simamora IP, Godron IP, Energiewende A. Understanding flexibility of thermal power plants: flexible coal power generation in the power system with higher renewable energy penetration. Report. Jakarta: Institute for Essential Services Reform; 2020.
[87] Hirst D, Keep M. Carbon price floor (CPF) and the price support mechanism. Report. London: House of Commons Library; 2018.
[88] Strategies for coal transition in Korea. Report. Paris: International Energy Agency; 2023.
[89] Notice on pilot projects for thermal power flexibility renovation. Report. Beijing: National Energy Administration of China; 2016. Chinese.
[90] Guiding opinions on improving the regulating capacity of the power system. Report. Beijing: National Energy Administration of China; 2018. Chinese.
[91] Implementation plan for national coal power unit renovation and upgrading. Report. Beijing: National Energy Administration of China; 2021. Chinese.
[92] Gharibvand H, Gharehpetian GB, Anvari-Moghaddam A. A survey on microgrid flexibility resources, evaluation metrics and energy storage effects. Renew Sustain Energy Rev 2024;201:114632.
[93] Fan H, Zhang Y, Su Z, Wang B. A dynamic mathematical model of an ultra-supercritical coal fired once-through boiler-turbine unit. Appl Energy 2017;189:654–66.
[94] Mertens N, Alobaid F, Starkloff R, Epple B, Kim HG. Comparative investigation of drum-type and once-through heat recovery steam generator during start-up. Appl Energy 2015;144:250–60.
[95] Cruz MR, Fitiwi DZ, Santos SF, Catalão JP. A comprehensive survey of flexibility options for supporting the low-carbon energy future. Renew Sustain Energy Rev 2018;97:338–53.
[96] VanderWijk P, Brouwer A, VandenBroek M, Slot T, Stienstra G, VanderVeen W, et al. Benefits of coal-fired power generation with flexible CCS in a future northwest European power system with large scale wind power. Int J Greenh Gas Control 2014;28:216–33.
[97] Xu C, Xu G, Zhao S, Dong W, Zhou L, Yang Y. A theoretical investigation of energy efficiency improvement by coal pre-drying in coal fired power plants. Energy Convers Manage 2016;122:580–8.
[98] Lin B, Liu Z. Could coal-fired power plants with CCS be an effective way for carbon neutrality in China? Jof Manage Sci Eng 2024;9:461–73.
[99] Fu C, Anantharaman R, Jordal K, Gundersen T. Thermal efficiency of coal-fired power plants: from theoretical to practical assessments. Energy Convers Manage 2015;105:530–44.
[100] Pelissari MR, Cañas SSM, Barbosa MO, Tassinari CCG. Decarbonizing coal-fired power plants: carbon capture and storage applied to a thermoelectric complex in Brazil. Results Eng 2023;19:101249.
[101] Fan JL, Fu J, Zhang X, Li K, Zhou W, Hubacek K, et al. Co-firing plants with retrofitted carbon capture and storage for power-sector emissions mitigation. Nat Clim Chang 2023;13:807–15.
[102] Schill WP, Pahle M, Gambardella C. Start-up costs of thermal power plants in markets with increasing shares of variable renewable generation. Nat Energy 2017;2:1–6.
[103] Ashkanani HE, Wang R, Shi W, Siefert NS, Thompson RL, Smith K, et al. Effect of power plant capacity on the CAPEX, OPEX, and LCOC of the CO_2 capture process in pre-combustion applications. Int J Greenh Gas Control 2021;109:103371.
[104] Pang Y, Chi Y, Tian B. Economic evaluation of flexible transformation in coal-fired power plants with multi price links. J Clean Prod 2023;402:136851.
[105] Garðarsdóttir S, Göransson L, Normann F, Johnsson F. Improving the flexibility of coal-fired power generators: impact on the composition of a cost-optimal electricity system. Appl Energy 2018;209:277–89.
[106] Meng Y, Cao Y, Li J, Liu C, Li J, Wang Q, et al. The real cost of deep peak shaving for renewable energy accommodation in coal-fired power plants: calculation framework and case study in China. J Clean Prod 2022;367:132913.
[107] Shrimali G. Managing power system flexibility in India via coal plants. Energy Policy 2021;150:112061.
[108] Flexibilisation of coal fired power plant India (2023). Report. New Delhi: Central Electricity Authority; 2023.
[109] Zhao Z, Hao Y. Cost optimization of renewable energy accommodation system based on flexibility renovation of thermal power units. Modern Electr Power 2024;41(2):326–34. Chinese.

[110] Lin L, Xu B, Xia S. Multi-angle economic analysis of coal-fired units with plasma ignition and oil injection during deep peak shaving in China. Appl Sci 2019;9:5399.
[111] Yang L, Zhou N, Hu B, Chen L, Xu F, Wang Q. Optimal scheduling method for coupled system based on ladder-type ramp rate of thermal power units. Proc CSEE 2022;42:153–64. Chinese.
[112] Yang Y, Zeng Y, Qin C, Wang C. Planning model for flexibility reformation of thermal power units for deep peak regulation. Autom Electr Power Syst 2021;45:79–88. Chinese.
[113] Cai Y, He X, Su Y, Ding B, Hu W, Yang Z. Economic research on thermal power unit peak regulation considering safety, environmental protection and compensation. Electric Power 2021;54:199–205.
[114] Yan X, Tong D, Zheng Y, Liu Y, Chen S, Qin X, et al. Cost-effectiveness uncertainty may bias the decision of coal power transitions in China. Nat Commun 2024;15:1–12.
[115] Efkarpidis N, Imoscopi S, Geidl M, Cini A, Lukovic S, Alippi C, et al. Peak shaving in distribution networks using stationary energy storage systems: a Swiss case study. Sustain Energy Grids Netw 2023;34:101018.
[116] Qi L, Zhao L, Zhang YQ, Jiang SQ, Lin XY, Ren YS. Computable general equilibrium analysis of neutral carbon trading scheme and revenue recycling impacts on income distribution in China. Humanit Soc Sci Commun 2024;11:1–12.
[117] Operating rules of northeast electric power auxiliary service market. Report. Beijing: National Energy Administration of China; 2020. Chinese.
[118] Akrami A, Doostizadeh M, Aminifar F. Power system flexibility: an overview of emergence to evolution. J Mod Power Syst Clean Energy 2019;7:987–1007.
[119] Ackermann L, Gabrek N, Zachmann B, Neitz-Regett A, Seifermann S. Cost–benefit analysis and comparison of grid-stabilizing energy flexibility options and their applications in relation to the German energy system. Renew Energy Focus 2024;49:100570.
[120] Northeast electric power ancillary services market operation rules. Report. Beijing: National Energy Administration of China; 2020. Chinese.
[121] Implementation rules for Shandong Province's electric power auxiliary service management. Report. Beijing: National Energy Administration of China; 2022. Chinese.
[122] Implementation rules for auxiliary service management of grid connected power plants in East China region. Report. Beijing: National Energy Administration of China; 2019. Chinese.
[123] Implementation rules for power auxiliary service management in Central China region. Report. Beijing: National Energy Administration of China; 2020. Chinese.
[124] Zou C, Xiong B, Xue H, Zheng D, Ge Z, Wang Y, et al. The role of new energy in carbon neutral. Pet Explor Dev 2021;48:480–91.