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Planning Coal Power Generation Transition Considering Multiple Alternatives with a Full Life Cycle Perspective

Weiran Li, *Graduate Student Member, IEEE*, Jiaxin Wang, *Graduate Student Member, IEEE*, Ershun Du, *Senior Member, IEEE*, Peng Wang, *Member, IEEE*, Ning Zhang, *Senior Member, IEEE*, Chongqing Kang, *Fellow, IEEE*

***Abstract*—The transition of coal power generation is critical for the net-zero carbon emission evolution of power systems. It profoundly affects and is affected by the development of other parts of the power system so that a source-grid-load-storage co-planning model is required for the analysis. This paper proposes an efficient linear-form coal power transition planning model for long-term and large-scale planning problems. It considers six coal power transition alternatives, including new installation, at-life retirement, early retirement, rehabilitation, flexibility retrofit, carbon capture and storage retrofit, and covers a full life cycle of coal power from the temporal scale. First, coal power generation is clustered according to type and age to reduce the complexity in decisions and constraints in the planning model. Second, six transition alternatives are universally modelled considering the age dynamics of coal power during the planning horizon. Finally, a multistage coal power transition planning model coordinated with the expansion planning of source-grid-load-storage is formulated. Case studies on 8-stage 31-bus real-world China's power system from 2020 to 2060 suggest the effectiveness of the proposed model. The transition path of coal power with the coordination of different transition alternatives and the changing role of coal power towards carbon neutrality are analysed.**

***Index Terms*—Coal power, generation and transmission expansion planning, retirement, rehabilitation, retrofit.**

Nomenclature

A. Abbreviations

CCS	Carbon Capture and Storage
VRE	Variable Renewable Energy
PSDR	Peak-shaving Demand Response
LSDR	Load-shifting Demand Response
UC	Unit Commitment
A&T	Age and Type
LP	Linear Programming

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Weiran Li, Jiaxin Wang, Peng Wang, Ning Zhang, Chongqing Kang are with the State Key Laboratory of Power Systems, Department of Electrical Engineering, Tsinghua University, Beijing 100084, China (e-mail: liwr23@mails.tsinghua.edu.cn; jiaxinwangthu@gmail.com; wangpeng2020@mail.tsinghua.edu.cn; ningzhang@tsinghua.edu.cn; cqkang@tsinghua.edu.cn).

Ershun Du is with the Laboratory of Low Carbon Energy, Tsinghua University, Beijing 100084, China. (e-mail: duershun@tsinghua.edu.cn).

B. Sets

$\mathcal{C}$	Set of coal power type clusters.
$\mathcal{C}^{\mathrm{CCS}}$	Set of CCS coal power type clusters.
Ψ_f^{FRTo}	Set of inflexible coal power type clusters that can be converted to flexible type cluster f after receiving flexibility retrofit.
Ψ_c^{CRTo}	Set of non-CCS coal power type clusters that can be converted to CCS type cluster c after receiving CCS retrofit.
$\mathcal{I}$	Set of power resource clusters.
$\mathcal{I}_n$	Set of power resource clusters in region n.
$\mathcal{G}^{\mathrm{UC}}$	Set of UC generation clusters.
$\mathcal{G}^{\mathrm{CCS}}$	Set of CCS generation clusters.
$\mathcal{S}$	Set of storage clusters.
$\mathcal{L}$	Set of transmission lines.
$\Gamma_n^{\mathrm{T/F}}$	Set of transmission lines ending at/starting from region n.
$\mathcal{D}^{\mathrm{PS/LS}}$	Set of PSDR/LSDR resource clusters.

C. Parameters

γ	Discount rate.
$c_{i,p}^{\mathrm{Inv}}$	Per-unit investment cost of power resources.
$c_{i,p}^{\mathrm{Retire}}$	Per-unit demolition cost of coal power resources.
$c_{i,p}^{\mathrm{Rehab}}$	Per-unit rehabilitation cost of coal power resources.
$c_{i,p}^{\mathrm{FR/CR}}$	Per-unit flexibility/CCS retrofit cost of coal power resources.
$\lambda_i^{\min}$	Minimum output rate of UC resources.
$T_i^{\mathrm{On}}/T_i^{\mathrm{Off}}$	Minimum startup/shutdown time of UC resources.
α_i	Maximum ramp rate within 10 minutes of UC resources.
ρ_i^{CCS}	Maximum capture rate of CCS thermal resources.
e_i	Carbon emission factor of thermal resources.
κ_i^{CCS}	Per-unit required power for carbon capture of CCS thermal resources.

σ_i^{CCS}	Basic CCS energy consumption of CCS thermal resources.
l_n	Loss rate of within-region grid.
$D_{n,t,d,p}$	Hourly typical day load demand.

D. Variables

$U_{i,p}$	Capacity of power resource cluster i at planning period p.
$U_{i,a,p}^{\mathrm{Age}}$	Capacity of coal power A&T cluster i with age range a at planning period p.
$U_{i,p}^{\mathrm{New}}$	Newly installed capacity of coal power type cluster i at planning period p.
$U_{i,p}^{\mathrm{AR}}$	At-life retirement capacity of coal power type cluster i at planning period p.
$U_{i,a,p}^{\mathrm{FR}}/U_{i,a,p}^{\mathrm{CR}}$	Capacity of coal power A&T cluster i with age range a at planning period p receiving flexibility/CCS retrofit.
$U_{f,a,p}^{\mathrm{FRTo}}$	Capacity increase of flexible coal power A&T cluster f with age range a at planning period p from flexibility retrofit.
$U_{c,a,p}^{\mathrm{CRTo}}$	Capacity increase of CCS coal power A&T cluster c with age range a at planning period p from CCS retrofit.
$U_{i,a,p}^{\mathrm{ER}}$	Early retirement capacity of coal power A&T cluster i with age range a at planning period p.
$U_{i,a,p}^{\mathrm{Rehab}}$	Rehabilitation capacity of coal power A&T cluster i with age range a at planning period p.
$U_{i,t,d,p}^{\mathrm{SU}}/U_{i,t,d,p}^{\mathrm{SD}}$	Startup/shutdown capacity of UC resources.
$G_{i,t,d,p}$	Online capacity of UC resources.
$P_{i,t,d,p}$	Output power of generation or PSDR.
$P_{i,t,d,p}^{\mathrm{CCS}}$	Additional carbon capture power consumption of CCS thermal resources.
$P_{i,t,d,p}^{\mathrm{Dis}}/P_{i,t,d,p}^{\mathrm{Cha}}$	Discharging and charging power of storage resources.
$P_{i,t,d,p}^{\mathrm{Dec}}/P_{i,t,d,p}^{\mathrm{Inc}}$	Decreased and increased power of LSDR.
$P_{l,t,d,p}^{\mathrm{F}}$	Active power flow of transmission line from the starting bus.
$P_{l,t,d,p}^{\mathrm{T}}$	Active power flow of transmission line to the ending bus.
$P_{i,t,d,p}^{\mathrm{Hot}}$	Spinning reserve capacity of UC resources.
$E_{i,t,d,p}^{\mathrm{CCS}}$	Carbon capture amount of CCS thermal resources.

I. Introduction

As the carbon emission reduction goals were brought up around the globe in many countries [1], the decommissioning of coal power has been proposed and actively discussed [2]. Although some countries with small coal power generation proportions have nearly completely phased out coal power, countries with coal power as the dominant generation still have a long way to go to retire and replace the existing emission-intensive coal power generation [3], [4].

However, it is not economical or safe for an abrupt and massive decommissioning of existing coal power units. Instead, a gradual transition path is more practical. Massive decommissioning of existing coal power units in current situation may cause high transitional costs, since most coal power units still have considerable remaining operating lifetime, which may result in high stranded loss once retired [5]. Moreover, a massive and abrupt coal power phase-out may increase the difficulty in power supply [6]. Technical breakthroughs have enabled coal power to operate in a more low-carbon and flexible way, which could keep existing generation installation status in phase with low-carbon transition requirements [7]. Recent newly installed units can be equipped with high-pressure and high-temperature resistant boilers and steam turbines, which can increase their generation capacity and efficiency in electricity generation [8]. Formerly built coal power units with small capacity and low efficiency can be forced to retire before reaching life expectancy, but this may cause high stranded loss [9]. A thorough rehabilitation for most coal power units reaching life expectancy can prolong their operating lifetime by 10 to 15 years [10]. Several retrofit actions, including flexibility retrofit and carbon capture and storage (CCS) retrofit, are also quite beneficial. Flexibility retrofit can achieve improvements in lower minimum output level, higher ramp rate, and shorter startup and shutdown time [11]. By capturing and storing carbon dioxide from power plants or factories, CCS technology can reduce carbon emissions by up to 90% [12].

Some researchers have studied unit-level coal power transition planning problem in recent years. In [13]–[15], the retirement planning of coal power is coordinated with the expansion planning of other generation, storage and wind, transmission and generation resources, respectively. But only retirement and new installation options are viable for coal power units. In [16], the retirement planning of coal units is achieved together with the expansion planning of variable renewable energy (VRE) and transmission. The age-related changes in units' performances, operation costs and reliability are achieved. However, it fails to consider other transition alternatives. In [17], retirement and rehabilitation of aging units are achieved together with the expansion planning of other generation resources. But the fact that only one alternative can be selected for each unit during the whole planning horizon limits the model applicable only to short-term planning. In [11], monthly retrofit planning and flexible operation of coal power units is modelled as a stochastic mixed-integer non-linear programming problem, and the non-linear formulations come from unit attribute modifications after retrofitting, which is difficult to solve. In summary, in these existing coal power transition planning studies, the transition alternatives for coal power are not fully developed, and they lack consideration of full life cycle modelling of coal power age dynamics. The large number of binary variables and constraints introduced during modelling force insufficient consideration of the expansion planning of other resources and over-simplified operation

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constraints, and also confine their applications to only small-scale planning problems.

It is challenging to efficiently formulate coal power transition planning model for two reasons. First, the modelling of multiple transition alternatives is challenging due to the complexity of decision-making and transition behaviours. The transition decisions for all coal power units are required to be made at each planning period, which need to be represented by separate decision variables. A large number of constraints are needed to model the transition behaviours including the changes in operation attributes, changes in operating lifetime and compatibility among different alternatives. Second, a long-term planning horizon is required for coal power transition planning to avoid shortsightedness. Therefore, a full life cycle modelling of coal power age dynamics is necessary in order to accurately estimate the operable years of coal power. However, the temporal coupling relationship between the age of coal power and the planning horizon makes it a challenging issue.

Moreover, the transition planning of coal power is required to be coordinated considered with source, grid, load and storage resources. First, adequate generation resources are needed to satisfy load demand with coal power gradually phasing out and load demand increasing rapidly [18]. Second, to accommodate the stochastic and volatile nature of VRE resources, more flexible resources including traditional flexible generation, transmission lines, demand response and storage are required [19]. Therefore, as the current dominant generation and potential future flexible resources, coal power's stay or go is vital to the safe and economical operation of power system. Thus, the transition of coal power should be coordinated with power resources from various aspects including generation, transmission, storage and demand-side resources. However, in many source-grid-load-storage co-planning studies, only single-stage planning is adopted, and only expansion planning is considered with no additional retirement or transition behaviours modelled [20]–[22]. It is challenging to efficiently formulate coal power transition planning within the source-grid-load-storage planning framework, for the already complex enough multistage expansion co-planning model requires the coal power transition planning formulation to be simple and concise. Some empirical studies on the low-carbon transition of China's power system adopt a multistage planning style and further depict the transition behaviours of coal power in their linear-form modelling. In [23], new installation and retirement for coal power are modelled, but age dynamics is not considered. In [24], new installation and retirement for coal power are modelled with age dynamics considered, but it fails to consider other feasible transition alternatives.

To address the existing research gap, we propose a linear-form coal power transition planning model considering six transition alternatives with a full life cycle perspective designed for long-term and large-scale planning problems. First, coal power generation is clustered according to type and age. Then, six transition alternatives including new installation, at-life retirement, early retirement, rehabilitation, flexibility retrofit and CCS retrofit are universally modelled. With the age dynamics of coal power carefully modelled, a full life cycle planning perspective is achieved. The model is integrated into an expansion co-planning model to form a multistage planning model considering the expansion planning of source-grid-load-storage and the transition planning of coal power.

The major contributions of this paper are summarized as follows.

1) A linear-form coal power transition model considering six transition alternatives with a full life cycle perspective is proposed. This model is incorporated with expansion planning model to form a multistage co-planning model considering the expansion planning of source-grid-load-storage and the transition planning of coal power for long-term and large-scale planning problems.
2) The transition path towards carbon neutrality of China's coal power generation from 2020 to 2060 obtained by real-world case studies is analysed.

The remainder of the paper is organized as follows. Section II introduces the coal power transition planning model. Section III presents the overall mathematical formulation of the multistage expansion and transition co-planning model. Section IV shows case study results on real-world China's power system from 2020 to 2060 to verify the effectiveness of the proposed model and discusses the results. Section V concludes the paper.

II. Coal Power Transition Planning Model

This section proposes a multistage coal power transition planning model, which can achieve the modelling of six transition alternatives with a full life cycle perspective. Coal power is first clustered according to their type and age. Based on this, coal power transition behaviours and age dynamics during planning are modelled. Then, the age-related transition costs are calculated.

A. Type and Age Clustering

To reduce the complexity of decisions and constraints at the planning level while maintaining the necessary information for making transition decisions, coal power generation in each region is clustered according to their type and age.

We first cluster the coal power units in each region according to their capacity and power generation technology, operation flexibility, and carbon capture capability into six types, as is shown in Fig. 1.

Units with different capacity and power generation technology mainly differ in power generation efficiency, which will be reflected through variable costs and per-unit carbon emissions. In this paper, units are classified according to capacity and power generation technology into two categories: units with capacity below 600 MW level and are not ultra-supercritical; units with capacity above 600 MW level and are ultra-supercritical. The latter category has lower variable costs and lower per-unit carbon emissions compared to the former one.

Units with flexible operation capability can achieve lower minimum output level, higher ramp rate and shorter startup/shutdown time, which enable flexible units to operate with a broader power output span and respond to power demand fluctuation more rapidly. In this paper, units are classified based on their flexible operation capability into

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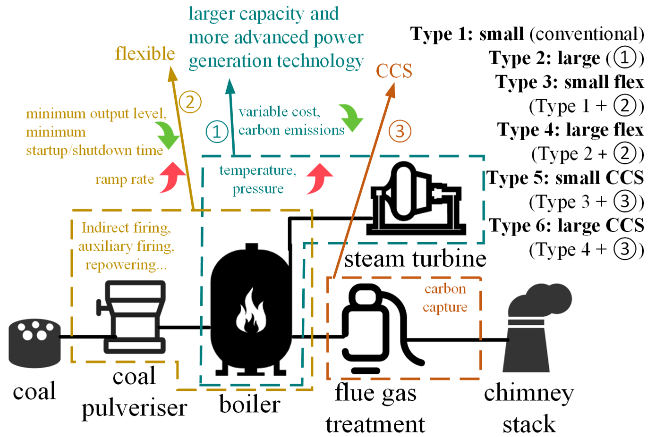

Fig. 1. Different types of coal power.

conventional and flexible categories. The operation of each type of coal power in each region is collectively modelled as a clustered unit through network-constrained relaxed clustered unit commitment method [25].

The power output bound constraints are as follows:

$$\lambda_i^{\min} G_{i,t,d,p} \le P_{i,t,d,p} \le G_{i,t,d,p}, \tag{1}$$

where $\lambda_i^{\min}$ is the minimum output rate of coal power type cluster $i \in \mathcal{C}$; $G_{i,t,d,p}$ and $P_{i,t,d,p}$ are the online capacity and output power of coal power type cluster $i \in \mathcal{C}$, respectively. Flexible coal power clusters have lower minimum output rate $\lambda_i^{\min}$ compared to conventional inflexible clusters.

The online capacity change constraints are as follows:

$$G_{i,t,d,p} - G_{i,t-1,d,p} = U_{i,t,d,p}^{\mathrm{SU}} - U_{i,t,d,p}^{\mathrm{SD}}, \tag{2}$$

where $G_{i,t,d,p}$ and $G_{i,t-1,d,p}$ are the online capacity of coal power type cluster i at time t and $t-1$ of typical day d at planning period p, respectively; $U_{i,t,d,p}^{\mathrm{SU}}$ and $U_{i,t,d,p}^{\mathrm{SD}}$ are the startup and shutdown capacity, respectively.

The minimum startup and shutdown time constraints are as follows:

$$G_{i,t,d,p} \ge \sum_{\tau=t-T_i^{\mathrm{On}}+1}^{t} U_{i,\tau,d,p}^{\mathrm{SU}}, \tag{3}$$

$$G_{i,t,d,p} \le U_{i,p} - \sum_{\tau=t-T_i^{\mathrm{Off}}+1}^{t} U_{i,\tau,d,p}^{\mathrm{SD}}, \tag{4}$$

where T_i^{On} and T_i^{Off} are the minimum startup and shutdown time of coal power type cluster i, respectively; $U_{i,p}$ is the capacity of coal power type cluster i at planning period p. Flexible clusters have shorter minimum startup and shutdown time compared to inflexible clusters. Their online capacities are less constrained by their previous startup and shutdown statuses, thus achieving a more flexible regulation.

As coal power units are mostly capable of ramping up or ramping down their power output from zero to maximum within an hour, which is the time resolution of our operation simulation. Therefore, ramp rate is reflected through 10-min spinning power reserve constraints, where the volatility of VRE output and load consumption is required to be offset by the real-time power increase response within 10 minutes.

The available power increase response of coal power within 10 minutes is as follows:

$$0 \le P_{i,t,d,p}^{\mathrm{Hot}} \le \min\{G_{i,t,d,p} - P_{i,t,d,p}, \alpha_i G_{i,t,d,p}\}, \tag{5}$$

where $P_{i,t,d,p}^{\mathrm{Hot}}$ is the spinning reserve capacity of coal power; α_i is the maximum ramp rate within 10 minutes for coal power type cluster $i \in \mathcal{C}$. Flexible clusters have higher ramp rate compared to inflexible clusters, thus can provide more power increase responses.

Units installed with CCS equipment have the capability to capture carbon emissions from their own combustion emissions. The following constraints model the carbon capturing behaviours of CCS coal power clusters.

The maximum carbon capture amount constraints are as follows:

$$0 \le E_{i,t,d,p}^{\mathrm{CCS}} \le \rho_i^{\mathrm{CCS}} e_i P_{i,t,d,p}, \tag{6}$$

where ρ_i^{CCS} is the maximum capture rate of CCS coal power type cluster $i \in \mathcal{C}^{\mathrm{CCS}}$; $E_{i,t,d,p}^{\mathrm{CCS}}$ is the carbon capture amount of CCS coal power type cluster $i \in \mathcal{C}^{\mathrm{CCS}}$; e_i is the carbon emission factor.

The additional carbon capture power consumption constraints are as follows:

$$P_{i,t,d,p}^{\mathrm{CCS}} = \kappa_i^{\mathrm{CCS}} E_{i,t,d,p}^{\mathrm{CCS}} + \sigma_i^{\mathrm{CCS}} U_{i,p}, \tag{7}$$

where κ_i^{CCS} and σ_i^{CCS} are the per-unit required power for carbon capture and basic energy consumption of CCS, respectively; $P_{i,t,d,p}^{\mathrm{CCS}}$ is the additional carbon capture power consumption.

Based on type clustering, coal power type clusters are further segmented by their age range. The age information is necessary for not only does making transition decisions need to consider the age factor, but transition decisions are required to be detailed to age.

In this paper, coal power clusters are segmented by age with the same time interval as the planning period interval. The same time interval setting is a crucial step in modelling the age dynamics of coal power, which will be described in more detail later. The designed operating lifetime of coal power is set as 30 years, which is the general case in China [10], and the age interval is set as 5 years. In this case, coal power clusters are segmented by age into 6 age ranges.

A demonstration of coal power type and age clustering is shown in Fig. 2, where the coal power generation in a single region in each planning period is represented by a 6×6 capacity matrix.

B. Relationship between Planning and Operation Level

At planning level, the planning decisions are made specific to each coal power type and age cluster, which is abbreviated as A&T cluster. During operation, the age specific information needn't be concerned, thus only type clusters are used at operation level.

The relationship between coal power type cluster capacity used for operation simulation, denoted as $U_{i,p}$, and the A&T

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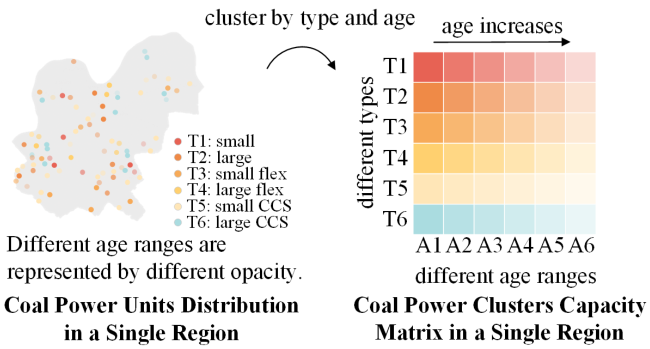

Fig. 2. Coal power type and age clustering.

cluster capacity used for transition planning, denoted as $U^{\mathrm{Age}}_{i,a,p}$, is given by:

$$U_{i,p} = \sum_{a=1}^{N_{\mathrm{A}}} U^{\mathrm{Age}}_{i,a,p}, \tag{8}$$

where $U^{\mathrm{Age}}_{i,a,p}$ is the capacity of A&T cluster i with age range a at planning period p; N_{A} is the number of age ranges.

C. Transition Alternatives Modelling

Based on the age and type clustering results of coal power generation, the transition behaviours of six transition alternatives are modelled.

Before introducing the mathematical modelling of transition alternatives, we first analyse the changes in coal power units and coal power A&T clusters after going through transitions. For new installation, new units are built; corresponding to a capacity increase in the A&T cluster with the first age range. For at-life retirement and early retirement, units with age reaching and before operating lifetime are retired, respectively; corresponding to a capacity decrease in the out-ranged A&T cluster and cluster with other age ranges, respectively. For rehabilitation, the remaining operable years of units are prolonged; corresponding to a certain amount of capacity decrease in the cluster with the corresponding age range and an exact amount of capacity increase in the cluster with a smaller age range with the prolonged operating lifetime as age interval. For flexibility retrofit and CCS retrofit, the operation attributes of units are improved; corresponding to a certain amount of capacity decrease in the corresponding cluster and an exact amount of capacity increase in the cluster with the same age range but improved attributes.

Given the analysis above, these six transition alternatives can be universally modelled. The transition decisions are made specific to each A&T cluster, modelled by capacity changes in one or two clusters.

To model the age dynamics of coal power, based on the same time interval setting of age range interval and planning period interval, age dynamics are modelled by progressing the age range of coal power A&T clusters by one interval between successive planning periods.

Here we introduce the mathematical formulation of coal power transition model.

New installation is modelled by:

$$U^{\mathrm{Age}}_{i,1,p} = U^{\mathrm{New}}_{i,p}, \tag{9}$$

where $U_{i,1,p}$ is the capacity of A&T cluster $i \in \mathcal{C}$ with the first age range at planning period p; $U^{\mathrm{New}}_{i,p}$ is the newly installed capacity of type cluster $i \in \mathcal{C}$ at planning period p.

Constraint (9) represents that the newly installed capacity in the corresponding planning period will be filled in the lowest age range.

At-life retirement is modelled by:

$$U^{\mathrm{AR}}_{i,p} = U^{\mathrm{Age}}_{i,N_{\mathrm{A}},p-1}, \tag{10}$$

where $U^{\mathrm{Age}}_{i,N_{\mathrm{A}},p-1}$ is the capacity of A&T cluster $i \in \mathcal{C}$ with age range N_{A} (the last age range) at planning period $p-1$; $U^{\mathrm{AR}}_{i,p}$ is the at-life retirement capacity of type cluster $i \in \mathcal{C}$ at planning period p.

Constraint (10) ensures that the highest age range capacity during last planning period will be at-life retired during this planning period.

The capacity increase constraints of flexible/CCS coal power clusters due to the flexibility/CCS retrofit of inflexible/non-CCS clusters are given by:

$$U^{\mathrm{FRTo}}_{f,a,p} = \sum_{i \in \Psi^{\mathrm{FRTo}}_{f}} U^{\mathrm{FR}}_{i,a,p}, \tag{11}$$

$$U^{\mathrm{CRTo}}_{c,a,p} = \sum_{i \in \Psi^{\mathrm{CRTo}}_{c}} U^{\mathrm{CR}}_{i,a,p}, \tag{12}$$

where $U^{\mathrm{FR}}_{i,a,p}$ and $U^{\mathrm{CR}}_{i,a,p}$ are the capacity of A&T cluster $i \in \mathcal{C}$ with age range a at planning period p receiving flexibility retrofit and CCS retrofit, respectively; $U^{\mathrm{FRTo}}_{f,a,p}$ is the capacity increase of flexible A&T cluster $f \in \mathcal{C}^{\mathrm{Flex}}$ with age range a at planning period p, and Ψ^{FRTo}_{f} is the set of inflexible type clusters that can be converted to flexible type cluster f after receiving flexibility retrofit; $U^{\mathrm{CRTo}}_{c,a,p}$ is the capacity increase of CCS A&T cluster $c \in \mathcal{C}^{\mathrm{CCS}}$ with age range a at planning period p, and Ψ^{CRTo}_{c} is the set of non-CCS type clusters that can be converted to CCS type cluster c after receiving CCS retrofitting.

Constraints (11) and (12) represent the capacity mapping relationship between different types of coal power clusters after retrofit.

The coal power continuity planning constraints are as follows, through which the capacity changes resulting from early retirement, rehabilitation, flexibility retrofit and CCS retrofit are calculated, and the age dynamics of coal power are modelled:

$$\begin{aligned} U^{\mathrm{Age}}_{i,a,p} &= U^{\mathrm{Age}}_{i,a-1,p-1} - U^{\mathrm{ER}}_{i,a,p} - U^{\mathrm{Rehab}}_{i,a,p} + U^{\mathrm{Rehab}}_{i,a+ex,p} \\ &\quad - U^{\mathrm{FR}}_{i,a,p} + U^{\mathrm{FRTo}}_{i,a,p} - U^{\mathrm{CR}}_{i,a,p} + U^{\mathrm{CRTo}}_{i,a,p}, a \geq 2, \end{aligned} \tag{13}$$

where $U^{\mathrm{Age}}_{i,a,p}$ and $U^{\mathrm{Age}}_{i,a-1,p-1}$ are the capacity of A&T cluster $i \in \mathcal{C}$ with age range a at planning period p and A&T cluster i with age range $a-1$ at planning period $p-1$, respectively. This represents that the age range of coal power capacity in last planning period will increase by one since age range and planning period have the same five-year time interval setting.

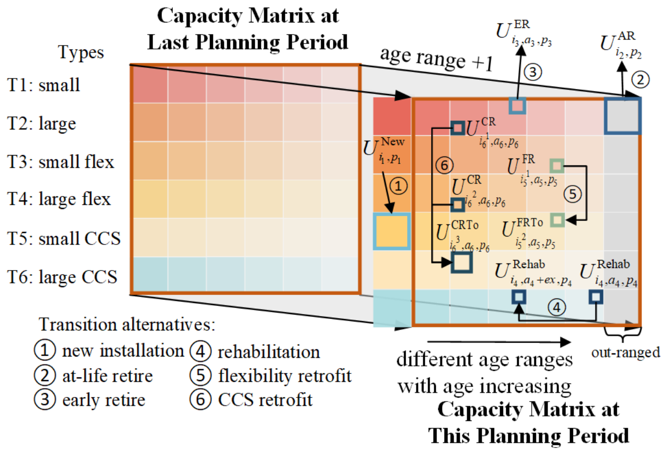

Fig. 3. Coal power transition process.

The second term on the right-hand side $U^{\mathrm{ER}}_{i,a,p}$ is the early retirement capacity. The third and fourth terms $U^{\mathrm{Rehab}}_{i,a,p}$ and $U^{\mathrm{Rehab}}_{i,a+ex,p}$ are the rehabilitation capacity of A&T cluster i with age range a and age range $a+ex$, respectively, where ex is a constant and equals to the prolonged age interval. This means the rehabilitation capacity is transferred from the corresponding age range to a smaller age range with prolonged operating lifetime as age interval. The last four terms $U^{\mathrm{FR}}_{i,a,p}$, $U^{\mathrm{FRTo}}_{i,a,p}$, $U^{\mathrm{CR}}_{i,a,p}$ and $U^{\mathrm{CRTo}}_{i,a,p}$ are the capacity receiving flexibility retrofit, capacity increase due to flexibility retrofit, capacity receiving CCS retrofit and capacity increase due to CCS retrofit, respectively. These terms denote the capacity transfer relationship between coal power clusters receiving the retrofit and converting to through retrofit, which denotes the technical upgrade after retrofit.

The overall transition alternative modelling is represented by the equations above. The transition process in a single region is illustrated in Fig. 3, where the modelling is achieved by capacity increase (new installation), capacity decrease (at-life retirement and early retirement), capacity transfer between age ranges (rehabilitation), capacity transfer between types (flexibility retrofit and CCS retrofit), and capacity transfer between planning periods with right-shifted age (aging).

Through our method, a detailed modelling of coal power transition behaviours and age dynamics are achieved. A full life cycle modelling during transition planning is fulfilled, through which coal power age dynamics can be tracked, the implementations of multiple transition alternatives at different planning periods can be achieved, and the transition alternatives taken during the full life cycle of coal power can be traced.

D. Transition Costs Calculation

The last step in modelling coal power transition from a full life cycle perspective is to carefully calculate the age-related transition costs. These transition costs are all annualized over the remaining operable years, and the costs within the planning horizon are included.

For A&T cluster $i \in \mathcal{C}$ with age range a during planning period p, the remaining operable years are calculated by:

$$L^{\mathrm{Remain}}_{i,a,p} = 5(N_{\mathrm{A}} - a + 1), \tag{14}$$

where $L^{\mathrm{Remain}}_{i,a,p}$ is the remaining operable years; N_{A} is the number of age ranges.

Its remaining operable years within the planning horizon are calculated by:

$$L^{\mathrm{Within}}_{i,a,p} = \min\{5(N_{\mathrm{A}} - a + 1), 5(N_{\mathrm{P}} - p + 1)\}, \tag{15}$$

where $L^{\mathrm{Within}}_{i,a,p}$ is the remaining operable years within the planning horizon. $5(N_{\mathrm{A}} - a + 1)$ is the remaining operable years. N_{P} is the number of planning periods, and $5(N_{\mathrm{P}} - p + 1)$ is the remaining planning years. $L^{\mathrm{Within}}_{i,a,p}$ is calculated by taking the minimum of remaining operable years and remaining planning years.

The new installation, rehabilitation, flexibility retrofit and CCS retrofit costs of A&T cluster $i \in \mathcal{C}$ with age range a during planning period p are calculated by:

$$C^{\mathrm{ALT}}_{i,a,p} = \frac{\gamma \sum_{y=1}^{L^{\mathrm{ALT,Within}}_{i,a,p}} (1+\gamma)^y}{1-(1+\gamma)^{-L^{\mathrm{ALT,Remain}}_{i,a,p}}} c^{\mathrm{ALT}}_{i,p} U^{\mathrm{ALT}}_{i,a,p}, \tag{16}$$

where the superscript ALT can denote the superscript New, Rehab, FR or CR, representing rehabilitation, flexibility retrofit and CCS retrofit transition alternatives, respectively. Notably, for new installation, only the first age range transition costs $C^{\mathrm{New}}_{i,1,p}$ exist. $L^{\mathrm{ALT,Remain}}_{i,a,p}$ and $L^{\mathrm{ALT,Within}}_{i,a,p}$ are the remainning operable years and remaining operable years within the planning horizon after the corresponding transition actions, respectively. For new installation, the values are $L^{\mathrm{Remain}}_{i,1,p}$ and $L^{\mathrm{Within}}_{i,1,p}$; for rehabilitation, the values are $L^{\mathrm{Remain}}_{i,a-ex,p}$ and $L^{\mathrm{Within}}_{i,a-ex,p}$; for flexibility retrofit or CCS retrofit, the values are $L^{\mathrm{Remain}}_{i,a,p}$ and $L^{\mathrm{Within}}_{i,a,p}$. γ is the discount rate; $c^{\mathrm{ALT}}_{i,p}$ is the per-unit transition cost; $U^{\mathrm{ALT}}_{i,a,p}$ is the transition capacity. The coefficient in front of the per-unit cost converts the one-time transition costs to the costs during the remaining operable years within the planning horizon.

The early retirement cost of A&T cluster $i \in \mathcal{C}$ with age range a during planning period p, denoted as $C^{\mathrm{ER}}_{i,a,p}$, is calculated as follows:

$$C^{\mathrm{ER}}_{i,a,p} = \frac{\gamma \sum_{y=5N_{\mathrm{P}}+5a-5p+1}^{5N_{\mathrm{A}}} (1+\gamma)^y}{1-(1+\gamma)^{-5N_{\mathrm{A}}}} c^{\mathrm{Inv}}_{i,p-a+1} U^{\mathrm{ER}}_{i,a,p} + c^{\mathrm{Retire}}_{i,p} U^{\mathrm{ER}}_{i,a,p}, \tag{17}$$

where $c^{\mathrm{Inv}}_{i,p-a+1}$ is the per-unit investment cost at the planning period when the early retired coal power is installed; $c^{\mathrm{Retire}}_{i,p}$ is the per unit demolition cost; $U^{\mathrm{ER}}_{i,a,p}$ is the early retirement capacity. The first term on the right-hand side calculates the stranded loss outside the planning period resulting from early retirement. The second term calculates the demolition costs.

The at-life costs consist only of demolition costs.

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The total transition costs of all these transition alternatives of type cluster i at planning period p, denoted as $C_{i,p}^{\mathrm{Trans}}$, is calculated by summing up all these costs:

$$C_{i,p}^{\mathrm{Trans}} = C_{i,1,p}^{\mathrm{New}} + C_{i,p}^{\mathrm{AR}} + \sum_{a=1}^{N_{\mathrm{A}}} (C_{i,a,p}^{\mathrm{ER}} + C_{i,a,p}^{\mathrm{Rehab}} + C_{i,a,p}^{\mathrm{FR}} + C_{i,a,p}^{\mathrm{CR}}). \tag{18}$$

III. Mathematical Formulation of the Overall Expansion and Transition Co-planning Model

The coal power transition planning model introduced in the previous section is incorporated with existing expansion planning model to form a multistage co-planning model considering the expansion planning of source-grid-load-storage and the transition planning of coal power. VRE and traditional generation resources, AC and DC transmission resources, energy storage, peak-shaving demand response (PSDR) and load-shifting demand response (LSDR) are considered.

The objective of this model is to minimize total power supply cost, which comprises investment, maintenance and operation costs in the whole planning horizon. The overall problem can be naturally divided in terms of different time resolutions into multiple yearly planning level and hourly operation level. At planning level, constraints imposed on resource capacity such as resource limitations and long-term whole system requirements are included. Hourly operation simulation of typical days selected by k-medoids clustering algorithm are embedded in the overall planning model.

The overall planning problem is a large-scale linear programming (LP) problem and can be efficiently solved by commercial optimization solvers.

A. Objective Function

The objective is to minimize the total power supply cost C^{Obj} as follows:

$$C^{\mathrm{Obj}} = \sum_{p}^{N_{\mathrm{P}}} \frac{1}{(1+\gamma)^{5p}} \Big(\sum_{i \in \mathcal{I} \setminus \mathcal{C}} C_{i,p}^{\mathrm{Inv}} + \sum_{i \in \mathcal{C}} C_{i,p}^{\mathrm{Trans}} + \sum_{i \in \mathcal{I}} C_{i,p}^{\mathrm{Mat}} + \sum_{i \in \mathcal{I}} C_{i,p}^{\mathrm{Power}} + \sum_{i \in \mathcal{G}^{\mathrm{UC}}} C_{i,p}^{\mathrm{Start}} + \sum_{i \in \mathcal{G}^{\mathrm{CCS}}} C_{i,p}^{\mathrm{CCS}} \Big). \tag{19}$$

Total costs consist of investment cost $C_{i,p}^{\mathrm{Inv}}$ of every non-coal resource cluster $i \in \mathcal{I} \setminus \mathcal{C}$, transition cost $C_{i,p}^{\mathrm{Trans}}$ of every coal power type cluster $i \in \mathcal{C}$, maintenance cost $C_{i,p}^{\mathrm{Mat}}$ of every resource cluster $i \in \mathcal{I}$, operating power related cost $C_{i,p}^{\mathrm{Power}}$ of every resource cluster $i \in \mathcal{I}$, start-up cost $C_{i,p}^{\mathrm{Start}}$ of every UC generation resource cluster $i \in \mathcal{G}^{\mathrm{UC}}$ and CCS capture cost $C_{i,p}^{\mathrm{CCS}}$ of every CCS resource cluster $i \in \mathcal{G}^{\mathrm{CCS}}$. γ is the discount rate, which is used to convert costs in different planning periods to the beginning of the planning horizon level. The calculation of costs other than the coal power transition costs can be found in [23] and will not be developed in detail here.

B. Planning Constraints

Planning constraints include maximum development constraints, manufacturing and installation capability constraints, capacity continuity constraints, coal power transition planning constraints, annual utilization hour constraints, natural gas consumption constraints, power reserve constraints and carbon emission pathway constraints.

For maximum development constraints, the installed capacity of power resources is constrained due to limited natural resources conditions. For manufacturing and installation capability constraints, new installation capacity is constrained by limited manufacturing and installation capability. The continuous installation constraints ensure that the capacity of non-coal resources will increase by the new installation amount between successive planning periods. Coal power transition planning constraints are previously shown in (9)-(13). The annual utilization hour constraints set the upper and lower limits on the annual utilization hours of generation resources due to limited natural energy resources and maintenance, and also to ensure that they can operate at a certain profitable level. The natural gas consumption constraints limit the annual natural gas consumptions in each region. The power reserve constraints ensure a certain reserve capacity level maintained by generation, storage and DC inter-provincial transmission network. The carbon emission pathway constraints set the whole power system's carbon emission budget for every planning period to achieve the carbon neutrality goal.

C. Operation Constraints

Operation constraints include power resources operation model, power balance constraints, spinning power reserve and inertia constraints.

For hydro power, their power output cannot exceed the installed capacity. For conventional UC generation resources, which include coal, gas, biomass and nuclear power, their UC and operation behaviours modelling are previously shown in constraints (1)-(4). For CCS thermal resources, including coal, gas and biomass CCS power, their carbon capturing behaviours are modelled by these previously introduced constraints (6)-(7). For wind and solar power resources, the actual output power cannot exceed the hourly maximum generation output which is acquired through k-medoids clustering method. For CSP resources, three CSP components including solar fields, thermal energy storage and power generation blocks are considered and modelled [26]. For transmission lines, a transportation model considering power losses is applied. In the transportation model, the power flow on the transmission line can be deployed freely within the rated capacity [27], and line losses can be considered as a fixed portion of power flow [28]. For storage resources, the charging and discharging behaviours of storage are modelled by the sequential relationship of energy and power, intra-day energy balance constraints, maximum power and energy constraints. For DR resources, the power response of both PSDR and LSDR are required to be within the maximum capacity range. For LSDR, the increased and decreased power response should be balanced within each typical day.

The hourly regional power balance constraints are given by:

$$\sum_{i\in\mathcal{G}\cap\mathcal{I}_n} P_{i,t,d,p} - \sum_{i\in\mathcal{G}^{\mathrm{CCS}}\cap\mathcal{I}_n} P^{\mathrm{CCS}}_{i,t,d,p} + \sum_{i\in\mathcal{S}\cap\mathcal{I}_n} (P^{\mathrm{Dis}}_{i,t,d,p} - P^{\mathrm{Cha}}_{i,t,d,p}) + \sum_{i\in\mathcal{D}^{\mathrm{PS}}\cap\mathcal{I}_n} P_{i,t,d,p} + \sum_{i\in\mathcal{D}^{\mathrm{LS}}\cap\mathcal{I}_n} (P^{\mathrm{Dec}}_{i,t,d,p} - P^{\mathrm{Inc}}_{i,t,d,p}) + \sum_{l\in\mathcal{L}\cap\Gamma^{\mathrm{T}}_n} P^{\mathrm{T}}_{l,t,d,p} - \sum_{l\in\mathcal{L}\cap\Gamma^{\mathrm{F}}_n} P^{\mathrm{F}}_{l,t,d,p} = \frac{1}{1-l_n} D_{n,t,d,p}. \quad (20)$$

The first term on the left-hand side is the output power of generation resources in region n. The second term is the power used for carbon capture. The third and fourth terms are the discharging and charging power of storage. The fifth term is the peak-shaving power of PSDR. The sixth and seventh terms are the decreased and increased power of LSDR. The eighth and ninth terms are the power transmitted to and from region i by transmission lines. On the right-hand side, l_n is the loss rate of within-region grid, and $D_{n,t,d,p}$ is the hourly typical day load demand acquired through k-medoids clustering method.

The spinning power reserve constraints represent the flexibility requirements during power system operation, where the volatility of VRE output and load consumptions are supported by the spinning capacity, which is defined as the available power increase response within 10 minutes. The inertia constraints require that the system online inertia level should be greater than the minimum system inertia requirement. The inertia of generation and storage are taken into account, which is calculated by multiplying the inertia constant with online capacity or installed capacity.

IV. Case Studies on China's Power System

A. System Description

We use a real-world China's power system from 2020 to 2060 as the test system [29]. We adopt most of the parameters in [29], and update some existing parameters including load demands and cost curves for solar and wind power. As the modelling of coal power transition and demand response are newly added compared to [29], some additional parameters including finer data on coal power and demand response costs are introduced. The planning horizon is from 2020 to 2060 and is divided by five years' interval into eight planning periods. Power system operation of each planning period is represented by the last year in each planning period. Twelve typical days consisting of one typical day in each month are selected using k-medoids clustering method from real-world year-round VRE and load data.

The system contains 71 existing AC transmission lines and 33 existing DC transmission lines. 67 candidate AC transmission lines and 35 candidate DC transmission lines are allowed to expand during planning. It contains 31 buses by aggregating each provincial-level grid in mainland China as an individual bus. Each bus contains eight types of generation resources including hydro, coal (including small capacity conventional coal power, large capacity conventional coal power, small capacity flexible coal power, large capacity flexible coal power, small capacity CCS coal power and large capacity CCS coal power), solar (including centralised and distributed PV), wind (including onshore and offshore wind), gas (including conventional and CCS gas power), nuclear, biomass (including conventional and CCS biomass power) and CSP; two types of energy storage resources including pump storage and battery storage; two demand-side flexible resources including PSDR and LSDR.

Real-world year-round 8760h VRE output curves and VRE resource data of each province are acquired from [30]. Real-world year-round 8760h load curves of each province are acquired from [31]. Real-world cost data, resource parameters and installed capacity in 2020 are used as input parameters [23]. The unit cost projection curves are referenced from ATB [32], and the load demand level is referenced from [33], [34]. The carbon emission budget curve is manually set while both satisfies the '3060' carbon emission commitment and total carbon emission budget based on a series of policy and scientific reports [29], [33]. The reserve capacity level is set according to the current reserve level in each province. The spinning reserve constraints are set so that the system has sufficient spinning capacity to support a 5% increase in hourly load demand and a 5% decrease in VRE output due to forecasting error within 10 minutes. The system inertia requirement is set to 70% of the whole country inertia level in 2020.

Case studies are implemented using MATLAB on a server with CoreTM i9-12900K@5.20 GHz CPU and 128 GB of RAM. This large-scale LP optimization problem with 10^6-level variables and 10^7-level constraints in size is solved with Gurobi 10.0.

B. Case Comparisons

Case comparisons with the coal power transition model in two existing literature [23], [24] and different case settings with fewer transition alternatives are conducted. The coal power transition models in two existing literature on the empirical study of national-scale power system long-term low-carbon transition pathways are constructed and compared, denoted as Model A [23] and Model B [24]. Three additional cases with fewer transition alternatives are set, denoted as Case Only New, Case New & Retire, and Case No New. Our complete model with all six transition alternatives is denoted as Case All Six.

Both Model A and Model B are in linear form, and only new installation and retirement are considered. In Model A, new installation and retirement are modelled by capacity increasement and capacity decreasement, respectively. The age dynamics are not modelled, so there are no distinctions between early and at-life retirement. Investment costs are calculated by summing up the annualized costs from the new installation planning period to the last planning period, implying the assumption that coal power will only expand, which is self-contradictory. In Model B, age dynamics is considered by making retirement decisions at each planning period detailed to when the coal power is installed, and the existing coal power is forced to retire at the end of their operational lifetime. This is a nearly perfect model when only new installation and retirement are considered, except for one defect that a portion of stranded costs in later planning periods are not accounted for.

As only new installation and retirement are considered in Model A and B, in order to make the results more comparable, they are compared with our complete model with six transition alternatives, denoted as Case All Six, and our partial model where only new installation, early retirement and at-life retirement are considered, denoted as Case New & Retire.

TABLE I
COMPARISONS ON COSTS AND SOLUTION TIME IN DIFFERENT MODELS

Model	Total cost (trillion CNY)	Solution time (min)
All Six	**37.47**	**266.98**
Model A	37.65	303.03
Model B	37.96	235.82
New & Retire	38.04	269.00

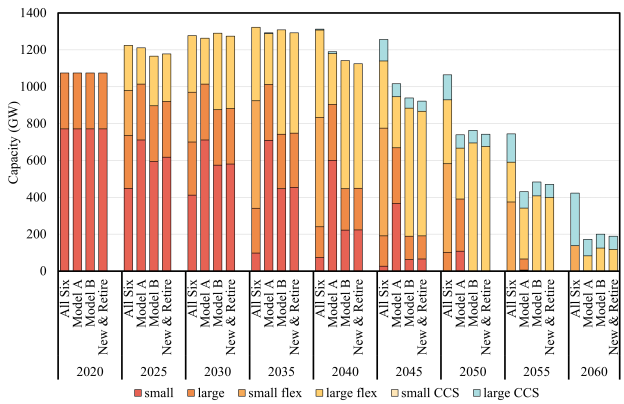


Fig. 4. Coal power capacity mix in different models.

Table I shows comparisons on costs and solution time in these four models. In Case All Six, the lowest total costs is achieved, and there is no significant increase in solution time. Fig. 4 shows a comparison on coal power capacity mix in these four models. The differences in results could correspond to the defects in Model A and Model B. The capacity results from our complete model greatly differ from other models, indicating that rehabilitation and retrofit alternatives have a significant role in coal power transition and cannot be ignored. Compared to Case New & Retire, in Model A, there are much more small capacity conventional coal power and much less large capacity flexible coal power in early stages. This is because with a lack of age dynamics modelling, model A fails to retire some of the formerly built old-aged small capacity conventional coal power in early stages. In later stages, the coal power capacity in Model A is much lower than Case New & Retire, resulting from a low share of advanced coal power in Model A. With age dynamics considered, the coal power capacity mix in Model B has little difference compared to Case New & Retire. However, the coal power capacity in Model B is almost always slightly higher than Case New & Retire. This is because with the stranded assets in later periods ignored in Model B, more coal power is newly installed in later periods, resulting in slightly higher coal power capacity.

Comparisons among cases with different transition alternative settings are conducted to verify the reasonableness of considering various transition alternatives in coal power transition planning. Four cases are set here. Case All Six includes all six transition alternatives introduced in this paper, and its results are thoroughly analysed in the following section. In Case Only New, only new installation is considered, which is the same setting as other resources. Case Only New is set to show that coal power needs to be treated differently in planning. In Case New & Retire, retrofit and rehabilitation settings are not considered, which is like the cases in many other coal power retirement planning models. In Case No New, the new installation of coal power is not considered, which is set to study the reasonableness of the recent controversial coal power new installation actions in China.

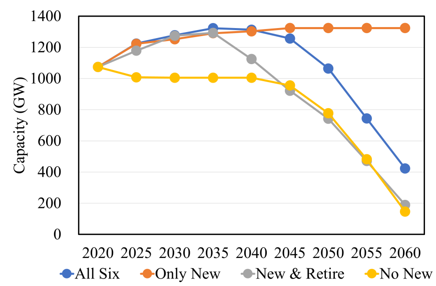


Fig. 5. Coal power capacity in cases with different transition alternative settings.

Fig. 5 shows the coal power capacity results of these four cases. The last three cases have notably different results from the first case. In Case All Six, coal power capacity first increases, subsequently maximizes in 2035, and decreases to a capacity level much lower than the initial value. In Case Only New, coal power capacity will keep increasing since only new installation are allowed. In Case New & Retire, the capacity results fit with Case All Six well during the first three planning periods but significantly differ in later periods. The reason is that rehabilitation actions will be actively adopted during the mid and later stages, which will be more thoroughly discussed later. In Case No New, coal power capacity will continue to decrease, since new installation is not allowed.

TABLE II
TRANSITION COSTS IN CASES WITH DIFFERENT TRANSITION ALTERNATIVE SETTINGS (TRILLION CNY)

Case	Total	Investment	Maintenance	Operation
All Six	**37.47**	**13.82**	**7.17**	**16.48**
Only New	40.23	12.99	7.08	20.16
New & Retire	38.04	14.61	7.22	16.22
No New	38.47	13.60	7.27	17.60

Table II shows the transition costs results of these four cases. Fig. 6 shows the capacity differences of resources between Case Only New, New & Retire, No New and Case All Six. Case All Six has the lowest total costs and Case Only New has the highest total costs. With more coal power installed, Case Only New has less need for solar, wind and storage, which results in smaller investment costs than Case All Six. But with more power generated by coal power, more expense will be spent on coal fuels and carbon capturing, thus

Fig. 6. Capacity differences between Case Only New, New & Retire, No New and Case All Six.

resulting in higher operation costs. In Case New & Retire, no rehabilitation option will lead to lower coal power capacity, so more other generation resources including solar and gas are required. No retrofit option will lead to lower coal power capacity and insufficient flexibility, so more storage will be needed to provide flexibility. The need for more solar, gas and storage will lead to higher investment costs. With less coal power installed, Case No New requires more solar and gas to compensate for the shortage in generation, and more transmission lines and storage for the shortage in flexibility. As more electricity will be generated by gas power, whose fuel costs and start-up costs are more expensive, higher operation costs will be needed.

To conclude, three other cases with incomplete transition alternatives have significantly different results in capacity and higher transition costs compared to Case All Six. This shows that adopting incomplete and limited transition alternatives setup in coal power transition planning will seriously deviate from real-world situations where various transition alternatives for coal power are available, and is less economical when abandoning other transition alternatives.

C. Coal Power Generation Dynamic Transition Process in a Selected Province

The coal power transition results of Shangdong Province are selected to illustrate the dynamic transition process of coal power, shown in Fig. 7. Shandong Province is selected because it has the largest coal power installed capacity in 2020, and the second largest coal power capacity in 2060. The coal power capacity in Shandong Province is 99 GW in 2020, peaking at 2030 with a total of 126 GW, then will reach 52 GW in 2060.

In Fig. 7, the coal power units in Shandong Province at each planning period can be represented by a 6×6 capacity matrix, and the transition matrices in between consecutive planning periods are also displayed to illustrate the transition alternatives adopted during these periods. Each transition matrix consists of two parts: one is the background matrix, which is acquired through right-shifted the capacity matrix in last planning period by one age range, representing the first term on the right-hand side of constraint (13); the other is the capacity changes from the adoption of various transition alternatives, representing other terms on the right-hand side of constraint (13). The collation results of the transition matrix equal to the capacity matrix at this planning period, representing the left-hand side term of constraint (13). The capacity change behaviours of each transition alternative can be observed on the transition matrices. For Shandong Province, no early retirement is adopted. Composite transition behaviours can be observed during some planning periods, where more than one transition alternatives are adopted for certain coal power in only one planning period, for instance, from 2055 to 2060, the flexible coal power with large capacity is first rehabilitated and then retrofitted into large capacity CCS coal power.

D. China's Coal Power Generation Transition Path Analysis

The type composition of installed coal power in each planning period can be acquired in Fig. 8. This figure is the Sankey diagram of coal power transition pathway, where the capacity transfer between consecutive planning periods, and the aggregated capacity changes resulting from each transition alternative are illustrated by the capacity flow between capacity bars. The energy generation, installed capacity, average utilization hours and age distribution results of coal power are displayed in Fig. 9. Coal power capacity will first continue to increase and reach a peak value of 1323 GW in 2035. Then, from 2035 to 2050, the installed capacity will gradually decrease, meanwhile coal power's overall technical level keeps upgrading, and conventional inflexible generation will be gradually replaced by flexible generation, which will account for over 90% of total coal power in 2050. From 2050 to 2060, the capacity will significantly decrease, leaving 423 GW of coal power in the system, which is only 39% of the initial coal power scale in 2020. Among the remaining coal power, over 67% will be equipped with CCS facilities. With little capacity newly installed in the future, coal power will be aging gradually, whose average operation time will change from 12 years in 2020 to 19 years in 2040 and finally 23 years in 2060. The average utilization hours of coal power will continue to decrease, while its energy generation will reach peak value in 2030 and gradually decrease since after.

Such significant transition in scale and structure of coal power is achieved by the coordination of various transition alternatives, as is shown in Fig. 8. Coal power will be newly installed only during the first four planning periods from 2020 to 2040 (very little from 2035-2040) with a total of 343 GW, and nearly all the newly installed generation will be large-capacity flexible type. Early retirement will mostly take place during the first planning period from 2020 to 2025 and the last two planning periods from 2050-2060 with a total of 125 GW, while much more coal power with a total of 869 GW will be at-life retired and the retirement will mostly take place in the last

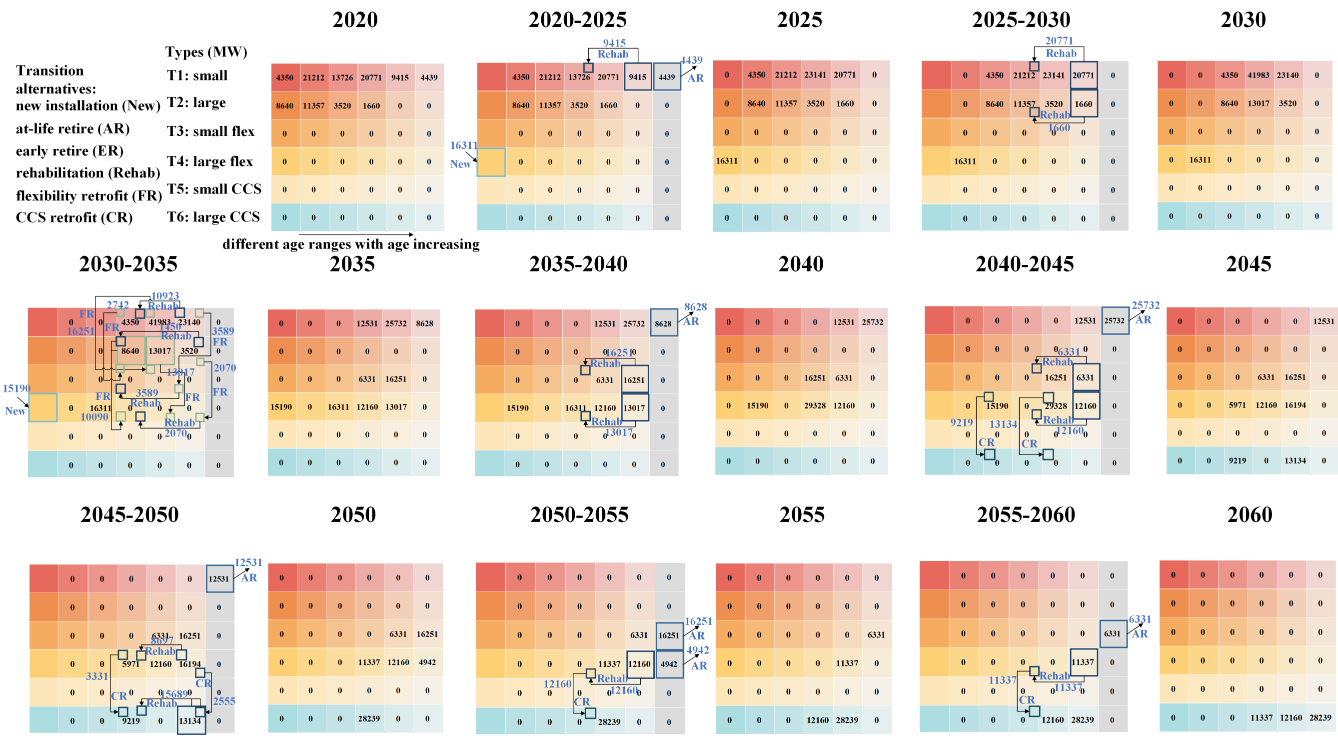


Fig. 7. The dynamic transition process of coal power in Shandong Province.

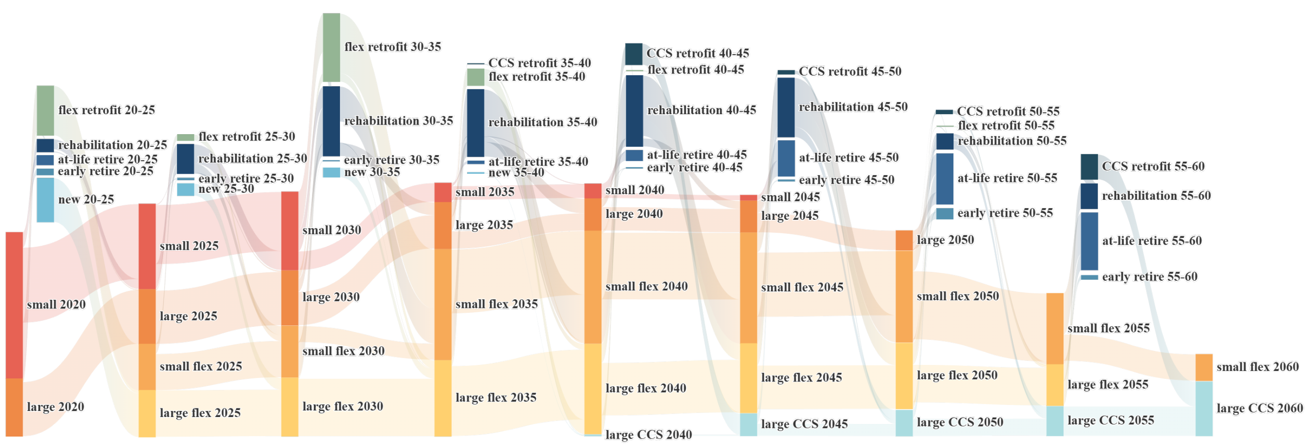
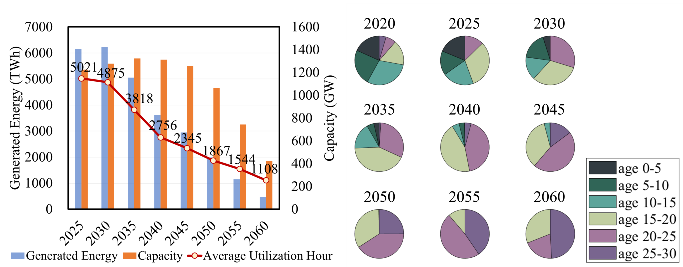


Fig. 8. The Sankey diagram of coal power transition pathway.



(a) Energy generation, capacity and average utilization hour

(b) Age distribution

Fig. 9. Coal power summarized transition results. (a) Energy generation, capacity and average utilization hours (b) Age distribution.

four planning periods from 2040 to 2060. Rehabilitation with a total of 1835 GW will be widely adopted during the whole planning horizon. As for the retrofit alternatives, flexibility retrofit and CCS retrofit will mostly be adopted during the first and second half of the whole planning horizon with a total of 739 GW and 281 GW, respectively. This shows that proper long-term overall planning can contribute to the full utilization of current coal power resources with little early retirement. Through long-term planning, a reasonable transition path which could well satisfy the low-carbon transition requirements utilising all feasible transition alternatives of coal power could be designed.

Coal power operation statistical results including online rate, reserve rate and average output level are shown in Fig. 10.

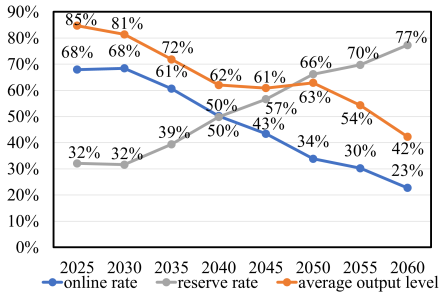


Fig. 10. Coal power operation statistical results.

Online rate and reserve rate refer to the percentage of online and offline coal power, respectively. The online rate of coal power will continue to decrease while the reserve rate will steadily increase, which means that in the future coal power will serve more as reserve power source. The average output level of online coal power displays a downward trend except for a slight increase in 2050. A lower average output level implies a stricter demand for coal power flexible operation capability.

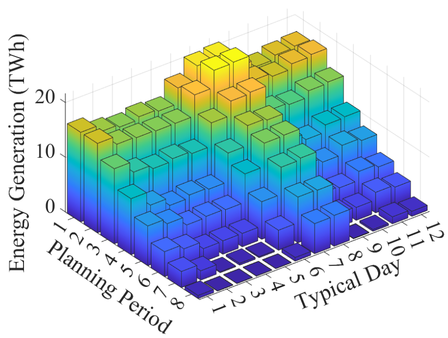


Fig. 11. Energy generation of coal power in each typical day.

The energy generation of coal power in each typical day is shown in Fig. 11. The general energy generation level in each planning period will gradually decrease. Moreover, there will be much more variation in coal power energy generation in different typical days during later planning periods, particularly in the last planning period from 2055 to 2060, over 3.3 and 3.4 times more energy will be generated in typical day 7 and 8 than any other typical days in that planning period, respectively. Such change in variation is closely related to the seasonal variation pattern of load consumption and VRE output.

V. Conclusion

This paper presents a coal power transition planning model considering six transition alternatives with a full life cycle perspective for long-term and large-scale strategic planning purpose. Coal power generation is first clustered according to type and age to reduce the complexity in decisions and constraints while maintaining the necessary information for transition planning. Based on the clustering results, six coal power transition alternatives including new installation, at-life retirement, early retirement, rehabilitation, flexibility retrofit and CCS retrofit are universally modelled, achieved by capacity increase, capacity decrease and capacity transfer operations of clusters. With the age dynamics of coal power during transition carefully modelled, a full life cycle perspective is achieved. This coal power transition model is in linear form, thus can be easily incorporated with existing expansion planning model to form a multistage co-planning model considering the expansion planning of source-grid-load-storage and the transition planning of coal power.

Case studies on real-world China's power system have shown the effectiveness of the proposed model through case comparisons. The low-carbon transition path of coal power from 2020 to 2060 is also obtained. With the coordination of various transition alternatives, the capacity of coal power will first increase and reach the peak value in 2035, subsequently decrease and leaving only 39% of the 2020's scale in 2060, with nearly two-thirds equipped with CCS facilities. The utilization hours of coal power will continue to decrease, and in the future, coal power will serve as reserve and flexible power source instead of providing day-to-day power supply.

References

[1] Climate Action Tracker. (2023) CAT net zero target evaluations. [Online]. Available: https://climateactiontracker.org/global/cat-net-zero-target-evaluations/

[2] M. Jakob, J. C. Steckel, F. Jotzo, B. K. Sovacool, L. Cornelsen, R. Chandra, O. Edenhofer, C. Holden, A. Löschel, T. Nace, N. Robins, J. Suedekum, and J. Urpelainen, "The future of coal in a carbon-constrained climate," *Nature Climate Change*, vol. 10, no. 8, pp. 704–707, Aug. 2020.

[3] Global Energy Monitor Wiki. (2024) Planning the end of coal-fired power: Phaseout targets and NDCs. [Online]. Available: https://www.gem.wiki/Planning_the_end_of_coal-fired_power:_Phaseout_targets_and_NDCs

[4] Global Energy Monitor. (2024) Global Coal Phaseout. [Online]. Available: https://globalenergymonitor.org/projects/global-coal-plant-tracker/coal-phaseout-tracking-retirements-and-paris-aligned-goals/

[5] R. Y. Cui, N. Hultman, D. Cui, H. McJeon, S. Yu, M. R. Edwards, A. Sen, K. Song, C. Bowman, L. Clarke, J. Kang, J. Lou, F. Yang, J. Yuan, W. Zhang, and M. Zhu, "A plant-by-plant strategy for high-ambition coal power phaseout in China," *Nature Communications*, vol. 12, no. 1, p. 1468, Mar. 2021.

[6] M. S. Alam, F. S. Al-Ismail, A. Salem, and M. A. Abido, "High-Level Penetration of Renewable Energy Sources Into Grid Utility: Challenges and Solutions," *IEEE Access*, vol. 8, pp. 190 277–190 299, 2020.

[7] Q. Li, "The view of technological innovation in coal industry under the vision of carbon neutralization," *International Journal of Coal Science & Technology*, vol. 8, no. 6, pp. 1197–1207, Dec. 2021.

[8] H. Fan, Z. Zhang, J. Dong, and W. Xu, "China's R&D of advanced ultra-supercritical coal-fired power generation for addressing climate change," *Thermal Science and Engineering Progress*, vol. 5, pp. 364–371, Mar. 2018.

[9] W. Zhang, M. Ren, J. Kang, Y. Zhou, and J. Yuan, "Estimating stranded coal assets in China's power sector," *Utilities Policy*, vol. 75, p. 101352, Apr. 2022.

[10] China Electricity Council. (2021) Study on flexibility operation and life extension operation of coal power units. [Online]. Available: https://cec.org.cn/detail/index.html?2-292230

[11] Z. Li, P. Yang, Z. Zhao, and L. L. Lai, "Retrofit Planning and Flexible Operation of Coal-Fired Units Using Stochastic Dual Dynamic Integer Programming," *IEEE Transactions on Power Systems*, vol. 39, no. 1, pp. 2154–2169, 2024.

[12] J. Fan, Z. Li, K. Li, and X. Zhang, "Modelling plant-level abatement costs and effects of incentive policies for coal-fired power generation retrofitted with CCUS," *Energy Policy*, vol. 165, p. 112959, Jun. 2022.

[13] Y. Tohidi, F. Aminifar, and M. Fotuhi-Firuzabad, "Generation expansion and retirement planning based on the stochastic programming," *Electric Power Systems Research*, vol. 104, pp. 138–145, Nov. 2013.

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[14] D. Liu, S. Zhang, H. Cheng, L. Liu, Z. Wang, D. Sang, and R. Zhu, "Accommodating Uncertain Wind Power Investment and Coal-fired Unit Retirement by Robust Energy Storage System Planning," *CSEE Journal of Power and Energy Systems*, vol. 8, no. 5, pp. 1398–1407, Sep. 2022.

[15] B. Chen and L. Wang, "Robust Transmission Planning Under Uncertain Generation Investment and Retirement," *IEEE Transactions on Power Systems*, vol. 31, no. 6, pp. 5144–5152, Nov. 2016.

[16] W. Shen, J. Qiu, K. Meng, X. Chen, and Z. Y. Dong, "Low-Carbon Electricity Network Transition Considering Retirement of Aging Coal Generators," *IEEE Transactions on Power Systems*, vol. 35, no. 6, pp. 4193–4205, Nov. 2020.

[17] M. Farhoumandi, F. Aminifar, and M. Shahidehpour, "Generation Expansion Planning Considering the Rehabilitation of Aging Generating Units," *IEEE Transactions on Smart Grid*, vol. 11, no. 4, pp. 3384–3393, Jul. 2020.

[18] B. Lin and Z. Liu, "Optimal coal power phase-out pathway considering high renewable energy proportion: A provincial example," *Energy Policy*, vol. 188, p. 114071, May 2024.

[19] E. Lannoye, D. Flynn, and M. O'Malley, "Evaluation of Power System Flexibility," *IEEE Transactions on Power Systems*, vol. 27, no. 2, pp. 922–931, May 2012.

[20] N. Zhang, H. Jiang, E. Du, Z. Zhuo, P. Wang, Z. Wang, and Y. Zhang, "An Efficient Power System Planning Model Considering Year-Round Hourly Operation Simulation," *IEEE Transactions on Power Systems*, vol. 37, no. 6, pp. 4925–4935, Nov. 2022.

[21] A. J. Conejo, Y. Cheng, N. Zhang, and C. Kang, "Long-term coordination of transmission and storage to integrate wind power," *CSEE Journal of Power and Energy Systems*, vol. 3, no. 1, pp. 36–43, Mar. 2017.

[22] N. Zhang, Z. Hu, B. Shen, S. Dang, J. Zhang, and Y. Zhou, "A source–grid–load coordinated power planning model considering the integration of wind power generation," *Applied Energy*, vol. 168, pp. 13–24, Apr. 2016.

[23] Z. Zhuo, E. Du, N. Zhang, C. P. Nielsen, X. Lu, J. Xiao, J. Wu, and C. Kang, "Cost increase in the electricity supply to achieve carbon neutrality in China," *Nature Communications*, vol. 13, no. 1, p. 3172, Jun. 2022.

[24] S. Chen, P. Liu, and Z. Li, "Low carbon transition pathway of power sector with high penetration of renewable energy," *Renewable and Sustainable Energy Reviews*, vol. 130, p. 109985, Sep. 2020.

[25] E. Du, N. Zhang, C. Kang, and Q. Xia, "A High-Efficiency Network-Constrained Clustered Unit Commitment Model for Power System Planning Studies," *IEEE Transactions on Power Systems*, vol. 34, no. 4, pp. 2498–2508, Jul. 2019.

[26] E. Du, N. Zhang, B.-M. Hodge, Q. Wang, C. Kang, B. Kroposki, and Q. Xia, "The Role of Concentrating Solar Power Toward High Renewable Energy Penetrated Power Systems," *IEEE Transactions on Power Systems*, vol. 33, no. 6, pp. 6630–6641, Nov. 2018.

[27] R. Romero, A. Monticelli, A. Garcia, and S. Haffner, "Test systems and mathematical models for transmission network expansion planning," *IEE Proceedings - Generation, Transmission and Distribution*, vol. 149, no. 1, pp. 27–36, Jan. 2002.

[28] Z. Zhuo, N. Zhang, Q. Hou, E. Du, and C. Kang, "Backcasting Technical and Policy Targets for Constructing Low-Carbon Power Systems," *IEEE Transactions on Power Systems*, vol. 37, no. 6, pp. 4896–4911, Nov. 2022.

[29] H. Wei, Z. Zhuo, N. Zhang, E. Du, J. Xiao, P. Wang, and C. Kang, "Transition path optimization and influencing factor analysis of carbon emission peak and carbon neutrality for power system of china," *Automation of Electric Power Systems*, vol. 46, no. 19, pp. 1–12, 2022.

[30] Global Energy Interconnection Development and Cooperation Organization, *Research on global renewable energy development and investment*. China Electric Power Press, 2020.

[31] National Development and Reform Commission. (2019) Typical power load curves in each provincial power system. [Online]. Available: https://www.ndrc.gov.cn/xxgk/zcfb/tz/201912/P020191230336066090861.pdf

[32] National Renewable Energy Laboratory. (2021) 2021 annual technology baseline electricity data. [Online]. Available: https://atb.nrel.gov/electricity/2021/data

[33] J. He, Z. Xie, and Z. Li, "A comprehensive report on china's long-term low-carbon development strategy and pathway," *China Population, Resources and Environment*, vol. 30, no. 11, pp. 1–25, 2020.

[34] Global Energy Interconnection Development and Cooperation Organization, "Research report on china's "14th Five-Year" power development plan," Tech. Rep., 2020.

Weiran Li (Graduate Student Member, IEEE) received the B.S. degree in electrical engineering in 2023 from Tsinghua University, Beijing, China, where she is currently working toward the Ph.D. degree with the Tsinghua University. Her research interests include power system planning, low-carbon power system, coal power transition.

Jiaxin Wang (Graduate Student Member, IEEE) received the B.S. degree in electrical engineering in 2022 from Tsinghua University, Beijing, China, where he is currently working toward the Ph.D. degree. His research interests include power system scheduling and planning, stability analysis and stability constrained optimization, and AI technique in power systems.

Ershun Du (Senior Member, IEEE) received the B.S. and Ph.D. degrees from the Department of Electrical Engineering, Tsinghua University, Beijing, China, in 2013 and 2018, respectively. He is currently an Associate Professor with Tsinghua University. His research interests include renewable energy uncertainty analysis, power system planning and energy policy.

Peng Wang (Member, IEEE) received B.S. and Ph.D. degrees from the Beijing Institute of Technology, Beijing, China, in 2014 and 2020 respectively. He is currently a Research Assistant Professor with Tsinghua University, Beijing, China. His research interests include power system planning with high penetration of renewable energy, and distributed optimization in distribution systems for grid power managements.

Ning Zhang (Senior Member, IEEE) received the B.S. and Ph.D. degrees from Tsinghua University, Beijing, China, in 2007 and 2012, respectively. He is currently an Associate Professor with Tsinghua University. His research interests include multiple energy systems integration, renewable energy, and power system planning and operation.

Chongqing Kang (Fellow, IEEE) received the Ph.D. degree from the Department of Electrical Engineering, Tsinghua University, Beijing, China, in 1997. He is now a Professor at the same university. His research interests include power system planning, power system operation, renewable energy, low-carbon electricity technology, and load forecasting.