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The importance of flexible hydropower in providing electricity stability during China's coal phase-out

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HIGHLIGHTS

- higher emission intensities of coal power plants running at below optimal efficiency to provide flexibility increases emissions from 3.4% to 11.1% depending on the region.
- The coal phase-out lowers flexibility indicators, with loss-of-load increasing in the full phase-out scenario in the absence of mitigating technologies such as electricity storage.
- Flexible hydropower eases peak demand issues significantly and the operating range of hydro-units has no significant effect on system flexibility or emissions.

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ABSTRACT

A rapid coal phase-out is critical if China is to achieve carbon neutrality by 2060. However, this presents a significant challenge in maintaining system flexibility as the number of coal power stations reduce and renewable energy penetration increases. Here we analyze the interactions between flexibly operating hydroelectric facilities in balancing the decommissioning of a typical 600 MW coal-fired power unit across three different provinces with different electricity mixes. Rather than using a constant parameter for the carbon emission intensity for coal, as used in previous studies, we use dynamic intensities across different output levels. Accounting for the higher emission intensities of coal power plants running at below optimal efficiency to provide flexibility increases emissions from 3.4 % to 11.1 % depending on the region. The coal phase-out lowers flexibility indicators, with loss-of-load increasing in the full phase-out scenario in the absence of mitigating technologies such as electricity storage. Flexible hydropower eases peak demand issues significantly and the operating range of hydro-units has no significant effect on system flexibility or emissions. Overall, hydropower shows large potential in supporting decarbonization while maintaining system flexibility, especially for coal-dominated countries with abundant hydropower resources.

1. Introduction

China has pledged to be carbon neutral by 2060 with a goal of limiting global temperature rise to 1.5 °C [1]. A rapid coal phase-out is essential in meeting this pledge and as of 2021, 71 % of electricity-related carbon emissions are driven by coal-fired units. In 2021, China had 2991 coal-fired units in operation, with an installed capacity of 1043GW accounting for 51 % of global coal power capacity [2,3]. Fig. 1 shows the total capacity, phase of development, and the carbon emissions of each province. The reduction of coal power generation during

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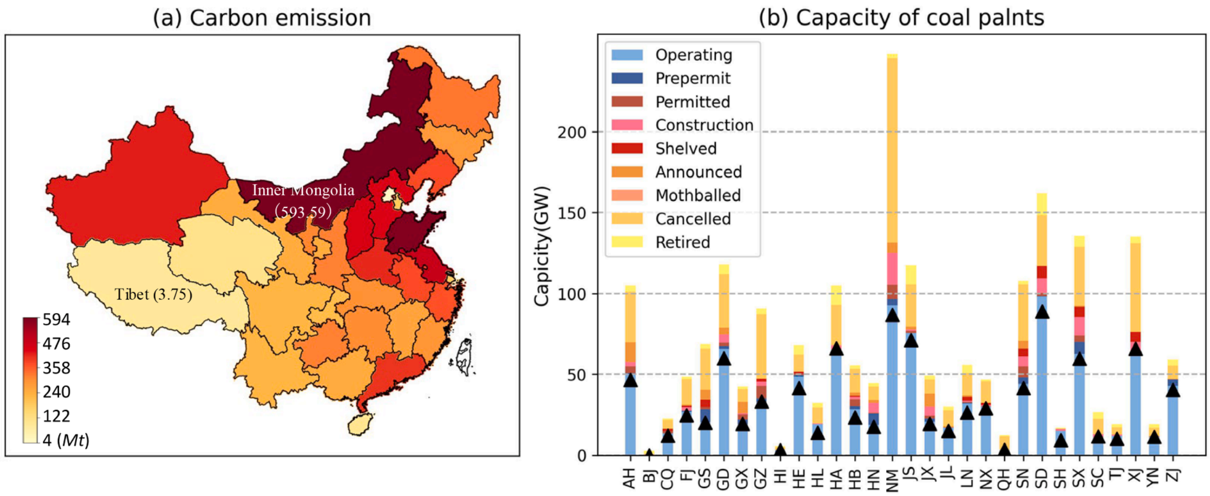


Fig. 1. (a) Provincial carbon emissions CO_2. (b) Installed coal capacity for each province where the stacked bar chart shows the phase of development (see appendix table S1 for province codes). Markers (in Black Triangles indicate the new capacity of coal-fired units installed between 2010 and 2020.

the phase-out will be offset predominately by renewable energy, mainly in the form of variable wind and solar (photovoltaic or PV) power. China has the world's largest installed capacity for both wind and PV generation, and their capacity will continue to increase rapidly over the next decade under carbon–neutral targets. Some estimates place China's installed wind and solar power capacity at 1200GW by 2026, four years earlier than its current target of 2030 [4].

Phasing out coal while increasing variable sources will bring two main challenges for electricity supplies. Firstly, as coal plants come offline, remaining coal units will be forced to increasingly adjust their output to balance wind and solar energy, resulting in more frequent load regulation and ramping of those remaining units. This will increase the operation of these units in non-optimal conditions (e.g. in rapid ramping to follow load) which would lower unit lifetime and increase remaining carbon emissions due to poorer combustion efficiencies [5,6]. In an extreme case, there may not be sufficient flexible power sources on the network that can match demand over necessary timescales (days, weeks, seasons, or years) [7].

Countries that plan to decommission coal-fired power units face above problems to varying degrees. They try to alleviate the pressure of inadequate flexibility through multiple means such as more flexible generation, demand response, or electricity storage systems. Hydropower will be the most economical and reliable option in the short-term energy transition for maintaining grid flexibility with higher levels of variable generation, especially for China, the United States, Brazil, India and other countries dominated by coal power and with abundant hydropower resources [8]. As an example, the Balkans will be replacing more than 30 % of their fossil fuel generated energy by 2030, and more than 95 % of their fossil fuel generated energy by 2050 [9]. Dams and reservoirs can store electricity in the form of water, which can be converted into electric energy, following load. Unlike other forms of generation such as coal or nuclear, hydropower can ramp rapidly. It is worth noting that the hydropower development in the above countries is nearly mature, and the construction of new hydropower stations will lead to higher time and economic costs. Therefore, tapping the flexibility potential from the existing hydropower stations rather than adding new hydropower capacity to mitigate the flexibility deficit caused by coal decommissioning is a more attractive option for decision-makers.

The role of hydropower in providing grid flexibility has been extensively studied, especially for smaller study areas such as an isolated system [10,11] or a part of a country [12]. Reference [13] based on residual load curve optimizes the annual operation curve of Akosombo reservoir, Ghana, and discusses the effect of hydropower on the integration of wind and solar. The results show that when the increase in electricity demand is less than 25 % and solar and wind energy are not contributing more than 20 % to the total electricity generation, the

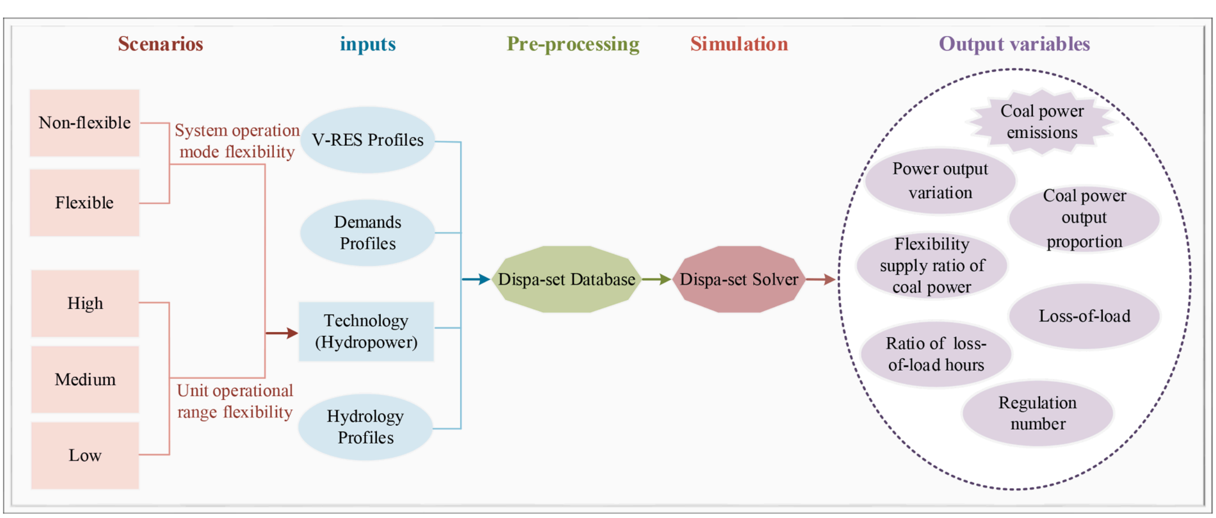
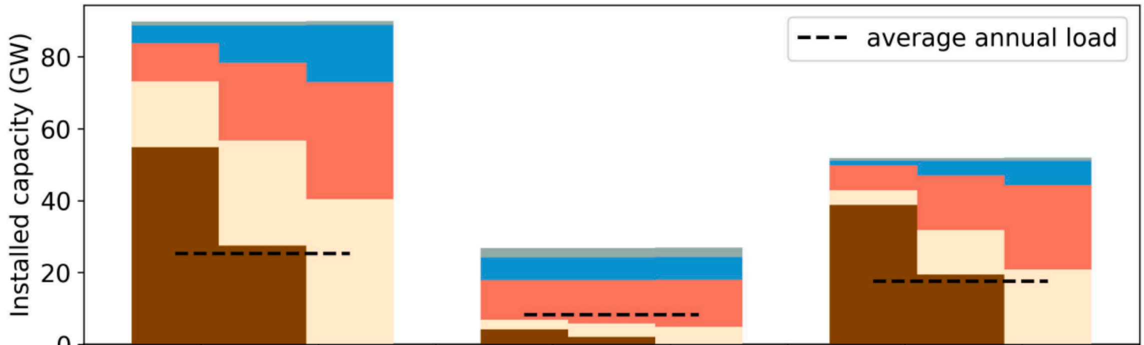


Fig. 2. Relational workflow between flexible variable and Dispa-set model.



	H-XJ	M-XJ	L-XJ	H-QH	M-QH	L-QH	H-SN	M-SN	L-SN
Run-of-river	1.05	1.05	1.05	2.59	2.59	2.59	0.77	0.77	0.77
Hydro	4.92	10.41	15.90	6.44	6.44	6.44	1.35	4.12	6.90
Solar PV	10.61	21.58	32.55	10.91	11.96	13.01	6.86	15.18	23.51
Wind	18.36	29.33	40.30	2.67	3.72	4.77	4.05	12.37	20.70
Coal	54.86	27.43	0.00	4.21	2.10	0.00	38.85	19.42	0.00

Fig. 3. Energy mixes in XJ, QH and SN during the coal phase-out (from CURRENT to HALF or to ZERO). The black dotted line provides the average annual load. The bottom table gives the installed capacity for various energy technology. Run-of-river is a further hydropower source but this is not dispatchable and so not considered flexible.

Akosombo hydropower reservoir can smooth out the variability of residual electricity demand. For the typical large hydropower bases in China, Reference [14] established a model considering the complex nonlinear constraints of hydropower and DC tie-lines. The results show that the proposed model can fully tap hydropower flexibility to meet sending-end and receiving-end power grids flexibility demands.

The relatively small research area and the small number of generation units in the above references cost less computing resources, so the hydropower modeling is capable of considering more detailed hydro-related characteristics, such as the nonlinear relationship between the water head, discharge and available generation level, and unit minimum stable output, hydrological inflow characteristics, and operation curves of the reservoir for various purposes (flood control and downstream agricultural irrigation demand, industrial use, shipping, etc). When considering a larger study area with more types of power generation resources and number of units. The technical details of hydropower mentioned above are ignored to a certain extent.

Several references have explored the role of hydropower in large-scale energy systems, especially in hydropower-rich countries. In reference [15], Norwegian hydropower was examined in the context of several future wind and solar power production scenarios in Central-West Europe, showing that hydropower could contribute to sharing flexibility with neighboring countries and balancing the power grid in the region. Reference [16] found that extending transmission access to hydro reservoirs reduces the need for coal-fired power plants. The transformation of the hydro-coal dominated energy system in South-eastern Europe also explores the effect of hydropower flexibility [9,17–22]. Reference [17] emphasizes that when designing the energy transition scenario in the Balkans in 2030, attention must be paid to the initial energy structure of the region, that is, it is a combination of hydropower and coal power. Reference [18] analyzed the impacts of different hydrological conditions on the power system in the Balkan Peninsula. According to the study, the cost of electricity increased from 17.79 €/MWh in dry years to 16.35 and 14.05 €/MWh in average and wet years as hydropower generation grew from 53.1 TWh to 65.2 TWh to 85.1 TWh. Reference [19] found that in the high RES 2030 scenario, most of the local demand from Bosnia and Herzegovina is covered by solar and wind power and balanced out by hydropower.

Essentially, all above studies model hydropower as a fully flexible generation resource, which is usually due to the lower start-up and ramp-up costs of hydro-units than coal-fired units in an energy system optimized for the lowest operating cost. As a result, hydro-units are

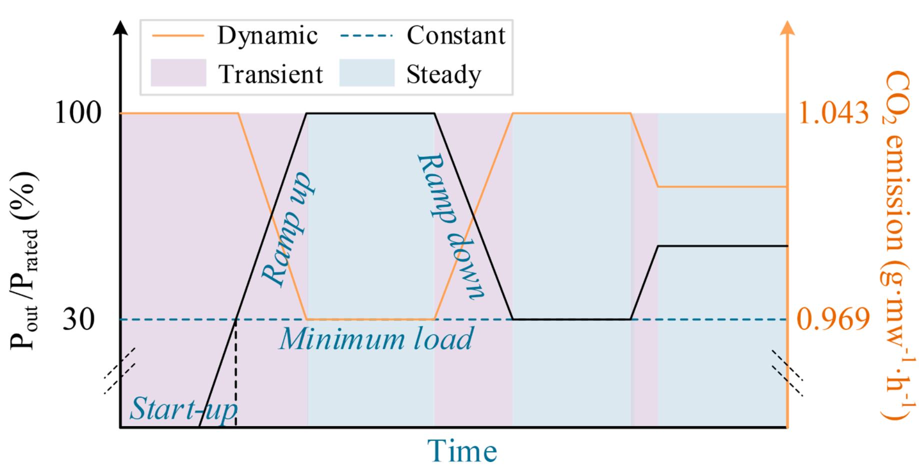


Fig. 4. Operating modes and corresponding carbon emission intensity of a typical 600 MW coal power unit [34]. The color blocks are used to distinguish whether the unit is in a steady-operational state or a transient-operational state. The orange solid line represents the dynamic emission intensity, which is inversely proportional to output. The blue dotted line shows that the constant emission intensity is independent of the operating conditions of the coal-fired power unit.

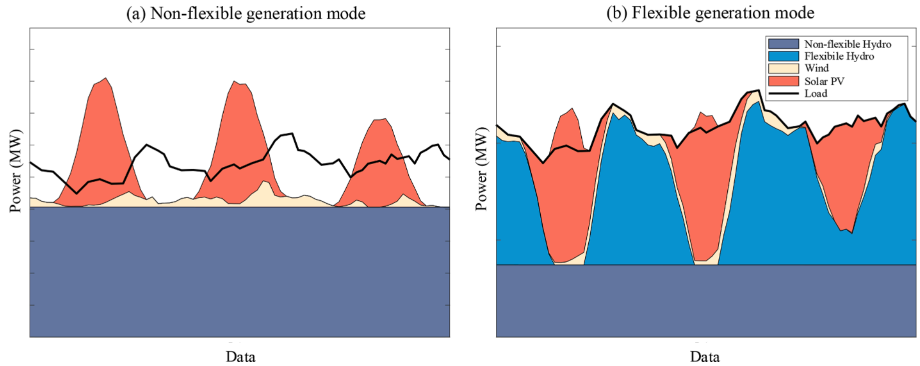


Fig. 5. Hydropower flexibility and reservoir scheduling curve. Hydropower operates in a non-flexible (base-load) manner in (a) while it is divided into a non-flexible part and flexible part in (b) to meet load demand while avoiding wind-solar curtailment.

superior to coal-fired units and become the preferred choice for power grid peak shaving. To a certain extent, this is inconsistent with the current operation status in some coal-based provincial energy systems in China, that a considerable number of hydropower plants provide a base-load role in the power grid. During the coal phase out, the base-load hydropower is bound to be converted into a flexible operation mode to provide peak shaving capabilities. In addition to the transition of the hydropower operation mode at system level, at unit level, the single hydro-unit will operate in a manner of expanding available operational range to provide greater power regulation flexibility. To the best of the authors' knowledge, studies on the impact of the expanding available operational range usually use dynamic models to focus on its impact on grid stability [23,24]. None of studies have investigated the impact of this expansion of operational range on hydropower and energy systems.

In addition, the above studies emphasize the advantages of hydropower flexibility in future energy transition scenarios, but ignore the costs brought by hydropower flexibility, such as the increase in the start-ups and the load-following. If this feature is not considered in future energy planning, the enthusiasm of power plant operators to participate in the energy transformation of hydropower will be greatly reduced, hindering the process of flexible operation of hydropower.

Hydropower's role in decarbonizing power systems is well documented in literature [25], which shows that 100 % decarbonization of the RE system in Sichuan province by 2030 is feasible. A 31-node hourly-resolved techno-economic optimization model was used in Reference [26] to study cost-optimal highly-renewable Chinese power systems. It turns out that if carbon emissions are reduced by more than 70 %, storage facilities such as hydropower are necessary to reduce system costs.

The above literatures relate carbon emissions intensity from coal generation using a constant emission coefficient, which underestimates the higher emissions caused by non-optimal (cycling and part load) operation of coal-fired units. Moreover, coal phase-out and rising wind and solar penetration will greatly increase this non-optimal operation in the remaining coal-fired units. Some literatures have proved through experiments and theoretical derivations that the difference in the dynamic coefficient of output and emission intensity of coal-fired units can significantly increase emissions per unit of electricity generated. For example, Dong et al. developed emission estimates for coal combustion for 600 MW and 300 MW units under deep cycle and regulated operation 720]. Blondeau et al. demonstrated the relationship between the unit's carbon emissions and power generation efficiency under different transient conditions and validated emissions under part load conditions, finding significantly higher emissions than under rated-load conditions [28]. Using dynamic coefficients will more accurately assess carbon emissions in the energy system.

This paper contributes to prior literature in three main ways. 1) we incorporate the dynamic carbon emissions of coal-fired units under non-optimal operation based on experimental data; 2) we investigate the impacts of system-level hydropower flexibility and unit-level operational range on hydropower and energy systems, and; 3) we estimate the carbon emissions, and system flexibility as coal generation is phased out and renewable energy increased.

This paper is organized as follows: Section 2 introduces the methodology describing the carbon emission model, the flexible hydropower model, data sources, geographic scope, and scenarios. Section 3 presents the results of the impact of coal phase-out, hydropower flexibility, and unit flexible operating range on decarbonization and system flexibility. Section 4 and 5 provide the conclusion and discussion of the work.

2. Materials and method

We isolate the influence of flexible hydropower operation on coal unit operation, and further quantify carbon emissions and grid flexibility indicators under the coal phase-out. We use an energy system optimization model based on one full year (8760 h) of results. We analyze three scenarios during the coal phase-out process: 1) a scenario based on today (CURRENT), 2) a scenario where half the coal capacity is retired (HALF), and 3) a full phase-out (ZERO). These scenarios are assessed under two operational conditions for hydropower, a flexible mode and non-flexible (base-load) mode. This aims to isolate the influence flexible hydropower can have on the overall system and results in 6 scenario variations (CURRENT, HALF, and ZERO for flexible and non-flexible modes). Under each scenario we report the operational constraints of the system and report emission and flexibility indicators (see appendix Eq.(s1-s5) for a full description of these indicators). Finally, the impact of flexibility at the single-unit level on emission and flexibility indicators is investigated. We outline the model components below.

2.1. Energy system model

We integrate an open-source energy system optimization model Dispa-set, a cost production model, a coupling economic dispatch model (ED), and a unit commitment model (UC) [29]. The model requires technical parameters for hydropower, including hydro-unit efficiency, ramp rate, start-up cost, and minimum operation time. It also considers the reservoir scheduling plan and reservoir storage capacity inflow characteristics (Fig. 2). Information on reservoir data are available in the

Suplementary Information.

The modelling approach consists of 5 steps: 1) build an input dataset based on flexible/variable load requirements, which is then 2) met by a set of potential energy generation and demand response options after which is 3) built into a unified database for the 4) Dispa-set Solver which optimizes the system and 5) returns the results. The operational mode (non-flexible & flexible) of hydropower units depends on the hydropower technology at the system and the unit operational range depends on hydro-unit technical operation parameters at the unit level. In addition, the wind and solar output, load demand time series and hydrology profiles are used as input files of the model. The emissions and flexibility characteristics of the interconnected energy system under different variables are then evaluated. The H, M, and L refers three hydro-unit flexibility cases, please see *section 3.3* for detail description.

2.2. Geographic scope and scenarios

To keep the results tractable and representative, we run the assessment for three regions with different characteristics, Xinjiang (XJ), Qinghai (QH) and Shaanxi (SN). XJ has an installed capacity far exceeding average load, QH has a high proportion of wind-solar capacity, and SN is dominated by coal power generation (see Fig. 3). We compared the changes in carbon emissions and energy system flexibility indicators during the coal phase-out. We assume that the three scenarios (CURRENT, HALF, ZERO) in each region share a standard load curve, and therefore the total installed capacity remains constant.

Three scenarios are investigated that roughly conform to a coal phase-out – current coal capacity (CURRENT) based on current energy data [30], a phase-out of half coal capacity based on the description below (HALF), and a full phase-out which is also based on the description below (ZERO). For XJ and SN, the reduced capacity of coal power in the HALF scenario and ZERO scenario is allocated to wind power, solar power, and hydropower in a 2:2:1 ratio based on approximate renewable resource availability [31]. For QH, the ratio is 1:1 of wind to solar since the installed capacity of hydropower is relatively high already (see Fig. 3 for full details).

2.3. Carbon emissions of the coal-fired unit in steady and transient operation

The standard approach is to calculate total carbon emissions from the primary energy consumption of an energy generator and then multiply by the specific, constant emission factor for that generation [32]. However, we allow for different emission factors for units under different operational modes (e.g. in peak load or rapid ramping) as recent studies have shown an increase in emissions during start-up and cycling [27,28]. For steady-state generation, the part-load carbon emission due to incomplete coal combustion is higher than rated-load emissions per unit of energy generated [33].

To identify the carbon emission characteristics of coal-fired units under different operating conditions a 600 MW coal-fired unit is used as they are very common in China. Typical operation and emission characteristics of a 600 MW unit are shown in Fig. 4. The operation of coal-fired power units can be divided into steady processes and transient processes, which are distinguished by the colored blocks in Fig. 4. Transient processes include start-up, ramp up, ramp down, and shutdown. Steady processes include part load and full load. Correspondingly, emissions resulting from transient processes are referred to transient-operation emissions, while emissions from steady process are referred to steady-operation emissions. We call the sum of transient-operation emissions and steady-operation emissions total emissions. The constant carbon emission intensity commonly used is 0.969 g·mw-1·h-1 while dynamic emission intensity is inversely proportional to output. Obviously, it is worth pointing out that previous studies that typically use the emissions intensity of 0.969 $g \cdot mw^{-1} \cdot h^{-1}$ during full load operation to calculate the total coal power plants emissions will underestimate emissions when being run in at sub-optimal output [34].

2.4. Data description

Load demand data are at hourly timestep over 2019 [30]. To isolate the effect of coal power on grid flexibility we assume that load demand in the control scenarios is the same as in the reference scenarios. This implies no change in demand response (start-up costs and other characteristics per technology are available in the appendix). The installed renewable energy capacity is shown in Fig. 3. The three provinces investigated have 37 reservoirs between them (see Suplementary materials for the reservoir capacity, unit head and unit capacity). Data for wind output are extrapolated from wind speed maps while PV production is calculated from temperature and solar radiation based on NREL data [35]. The cut-out and cut-in wind speeds are taken for a turbine with rated capacity of 1.5 MW using a wind turbine output model [36]. The capacity factor of photovoltaic solar of 1 MW rated capacity is calculated through a photovoltaic output model [37] (see appendix for further details).

2.5. Hydropower modeling

Hydropower plays a matching role in electricity grids in several different ways as wind and/or solar penetration increases. Moving from a non-flexible (base-load) mode (Fig. 5a) to a load-following flexible mode (Fig. 5b) limits renewable energy curtailment while securing supply. Ultimately, the available technical hydropower capacity is limited by reservoir level but there are several other concerns than simple capacity, including water needs to meet environmental requirements, downstream navigation, and irrigation. The characteristics of the hydropower plants investigated here are given in Suplementary Information (please see [29] for further modeling steps).

As a flexible source, hydropower needs to adjust its output according to net load fluctuation. The net load is calculated as:

$$P_{netload}(t) = Load(t) - CP_{wind}(t)^{*}P_{wind} - CP_{solar}(t)^{*}P_{solar} - CP_{ROR}{}^{*}P_{ROR} \quad (1)$$

Where the *CP* is the capacity factor of intermittent energy, subscript *ROR* represents the run of river power, whose power outputs only relates to the inflow and is not flexible.

The boundary conditions for reservoir capacity are the minimum and maximum storage capacities and the discharge is limited by real-time reservoir capacity during the optimization process:

$$\frac{Power(t)}{DischargeEfficiency} + StorageOutflow(t) + Spillage(t) - StorageInflow(t) \leq StorageCapacity(t) \quad (2)$$

To avoid empty reservoirs, the real-time storage reservoir capacity must take a given annual storage capacity scheduling curve as the lower boundary. Dispa-SET provides three Midterm Hydro-Thermal Scheduling (MTS) No-MTS, Zonal MTS, Regional MTS to help obtain storage capacity scheduling curve. We have adopted the No-MTS mode, that is, all storage capacity scheduling curve are determined by a separate external file. This is because the reservoir operation in China adopts the principle of determining hydropower generation by the amount of available water in the reservoir, not by electricity demand determines water consumption. Therefore, the storage capacity scheduling curve is basically determined by the regulation type of reservoir, flood control and downstream irrigation needs. The storage capacity scheduling curve of annual regulating reservoirs drops to the lowest level during the flood season in July and August. The weekly regulating reservoir undertakes the task of generating electricity from Monday to Friday, and stores water on Saturday and Sunday, as shown in Fg. s1.

When curtailment occurs, the ramp down from coal power plant can only absorb part of the curtailed wind and solar power, and further curtailment needs to be absorbed through shutting down the non-flexible (base-load) hydro-units.

$$StorageCapacity(t) \geq \min(ReservoirCurve(t))*StorageCapacity(t), StorageCapacity(0) + \sum_{h=1}^{N} InFlows(t) \quad (3)$$

Different structural characteristics and the layout of the hydropower system determine the reliable operational range and the minimum output limit of the turbine [23]. Here we assume a Francis turbine as they dominate in hydropower installation. Statistically, the minimum output limit of the Francis turbine in China varies between 35 % and 75 % of the rated capacity. We chose three cases of hydro-units operating ranges, H case (operating at 35–100 % of the rated power), M case (operating at 50–100 % of the rated power), and L case (operating at 65–100 % of the rated power) to explore the impact of unit-level flexibility parameters on carbon emissions and system flexibility.

3. Results

3.1. Impact of non-flexible hydropower on decarbonization and system flexibility

We first analyze the impact of operating hydropower in a non-flexible (base-load) mode to provide a baseline against which to compare the flexible operation. Typical monthly power dispatch (March 1st to April 1st) in the non-flexible (base-load) hydropower mode is shown in Fig. 6. In the CURRENT and HALF scenarios in XJ, hydropower maintains a steady output throughout the year with an average power of 2,462 MW and 5,705 MW, respectively. In the HALF scenario, coal phase-out means hydropower is the only dispatchable resource with hourly outputs between 8,448 MW and 16,896 MW. In QH, with an increase in the proportion of wind and solar, non-flexible (base-load) hydropower participates in power regulation. This is determined by the lower coal capacity and higher wind-solar capacity of QH energy system.

Previous studies have underestimated carbon emissions by assuming constant emission intensities at rated output. Table 1 shows the total emissions and the emissions generated in transient-operation (see Fig. 4) of coal-fired power units while taking this into account. By using a dynamic emission factor based on operating conditions we find higher total emissions than by assuming a constant emission factor. Increases are 8.5 % in XJ, 3.4 % in QH, and 11.1 % in SN, (see Table.1).

Combined with the cumulative emission curve in Fig. 7(a), the emissions in XJ and QH for the HALF scenario see large reductions compared to CURRENT scenario, by 41.3 % and 37.8 %, while SN only decreased by 24.5 %. SN is an interesting exception where coal power plants in the transient-operation mode emits a greater amount in the HALF with 5.23Mt than the CURRENT scenario with 4.274 *Mt*, as also shown in Fig. 7(b). As transient-operation emissions are exclusively a result of transient-operation processes (start-up, load increase and decrease, shutdown) in coal power generation, we present a curve in Fig. 7(c) that represents the output variation of coal power in two consecutive hours (see appendix Eq.(s1) for indicators definition and calculation). The results show that the output variation range of coal power in HALF scenario is larger than that in CURRENT scenario, which leads to larger transient-operation emissions.

The rising penetration of wind and solar challenges grid flexibility. To quantify this, grid flexibility performance under coal phase-out is quantified using indicators: coal power output proportion, flexibility supply ratio of coal power, loss-of-load, and ratio of loss-of-load hours (see appendix Eq.(s2-s5) for indicators definition and calculation).

When no hydropower is available, we find that loss-of-load increases dramatically as we move to the ZERO scenario (see Fig. 8). Coal power capacity in the HALF scenario is naturally 50 % of the CURRNET

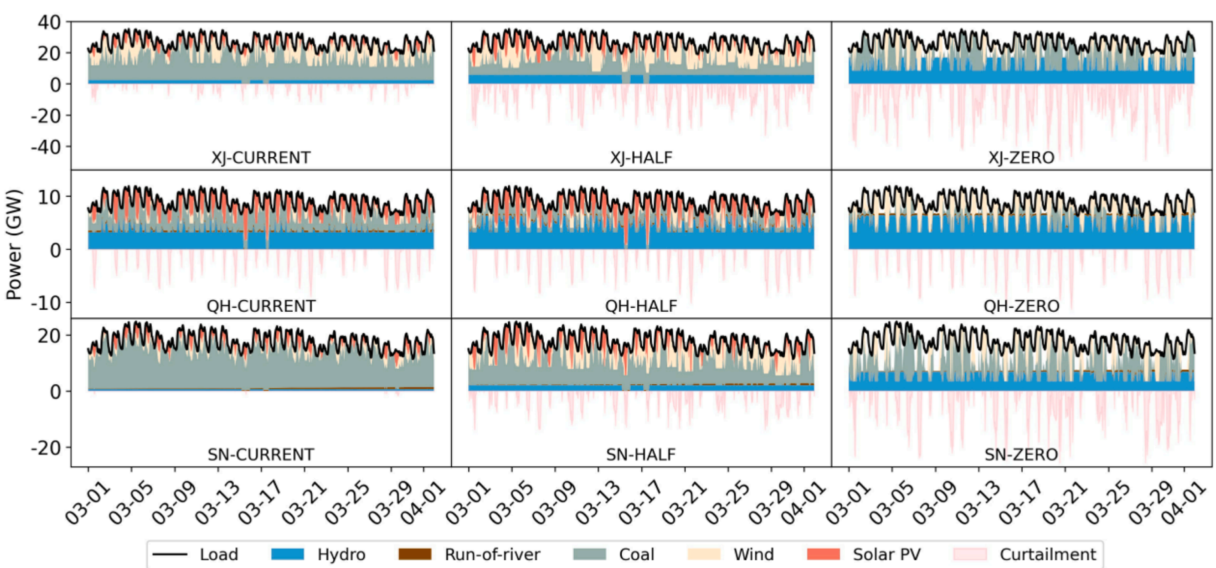


Fig. 6. Power dispatch for the three provinces for one month (top, middle, and bottom) with non-flexible (base-load) hydropower. CURRENT, HALF, and ZERO scenarios are shown from left to right. Negative power shows curtailed generation that would have been available if storage or faster reacting dispatchable generators were available.

Table 1
Carbon emissions using constant and dynamic emission coefficients during phase-out. Total gives the total emissions for the year, including transient-operation emissions and steady-operation emissions. Transient-operation emission gives the emissions from the transient-operation (start-up, ramp up, ramp down, and shut-down) of a coal-fired power plant (see Fig. 4).

		XJ		QH		SN	
		CURRENT	HALF	CURRENT	HALF	CURRENT	HALF
Total emissions	Constant	129.5	77.7	15.6	9.6	97.0	77.1
	Dynamic	140.6	82.5	16.1	10.0	107.7	81.4
Transient-operation emissions	Constant	8.43	6.23	0.90	0.42	3.81	4.95
	Dynamic	9.17	6.62	0.93	0.43	4.27	5.23

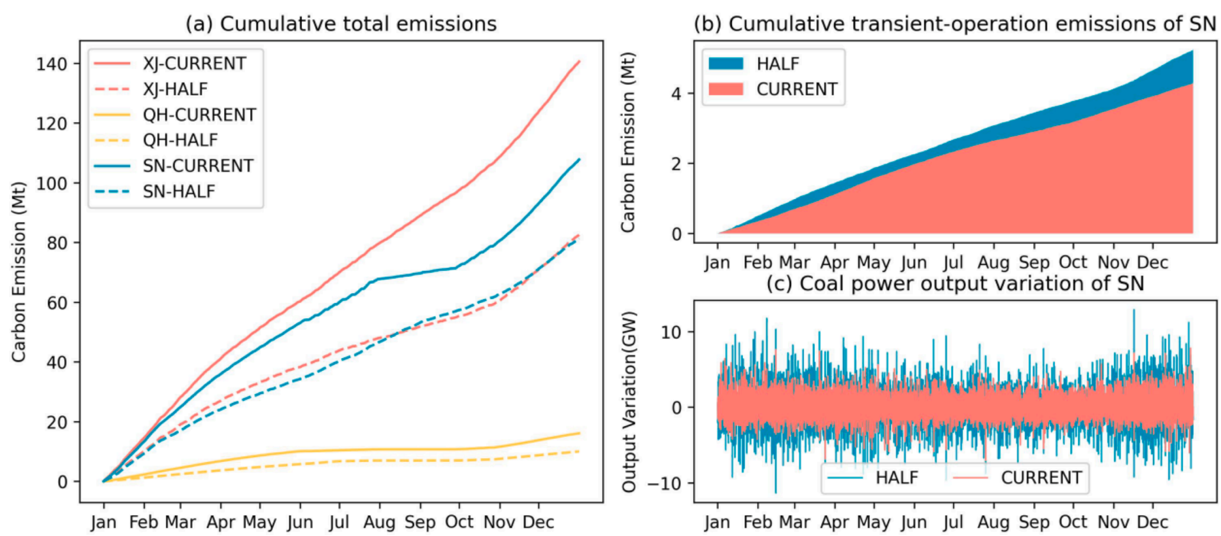


Fig. 7. Cumulative carbon emissions and coal power output variation over the year. (a) Cumulative total carbon emission. (b) Cumulative transient-operation carbon emission of SN. (c) Coal power output variation (see appendix Eq.(s1) for indicators definition and calculation) of SN.

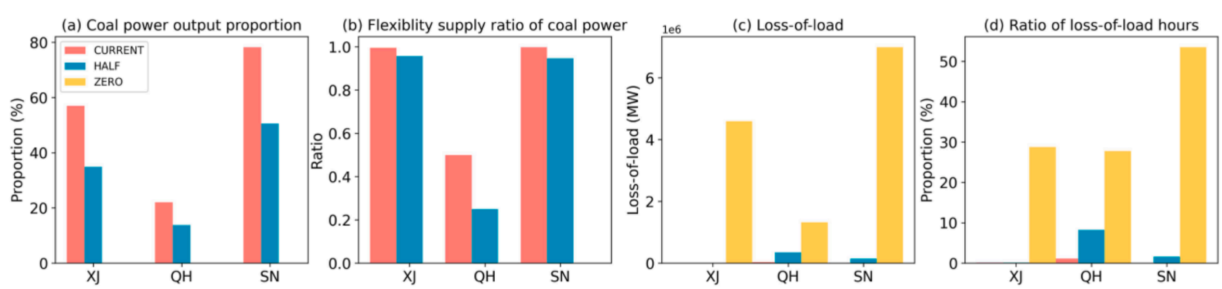


Fig. 8. Flexibility indicators of energy system during the coal phase-out process (see appendix Eq.(s2-s5) for indicators definition and calculation). (a) represents the proportion of electricity generated by coal in the total. (b) shows the proportion of coal power output in net load demand. (c) gives the total amount of the system loss-of-load. (d) shows the number of loss-of-load hours as a percentage of the total number of hours for the year.

scenario but the generation in the HALF scenario exceeds 50 % of the CURRENT scenario due to the requirement to balance the grid in the HALF scenario. Declining coal power capacity decreases the flexibility supply ratio, especially in QH, decreasing from 0.56 to 0.28. This is easily seen in subfigures (c) and (d) in the sharp increase in loss-of-load and loss-of-load hours proportion. In the ZERO scenario, loss-of-load-hours in XJ, QH and SN reach 28.7, 27.8, and 53.6, respectively. Next, we explore how flexible hydropower operation modes can help meet flexibility requirements and avoid the flexibility issues shown in Fig. 8.

3.2. Impact of flexible hydropower on decarbonization and system flexibility

We first present the difference hydropower can make under flexible and non-flexible (base-load) operations to the loss-of-load and other flexibility issues above. The differences in operating mode are shown in Fig. 9.

The typical weekly output in the HALF scenario clearly shows the impact on coal power output across all three provinces. Hydropower takes the role of load-following generation, reducing coal requirements. As the right-hand column shown in subfigure (b), (d) and (e) of Fig. 9, hydropower reduces its own output to integrate more wind and solar-PV power into the grid. To quantify the effect of flexible hydropower on hydropower and coal power output we introduce the concept of *regulation number* - when the hydro-unit or coal unit output is different within two consecutive hours, it is deemed that one regulation process has been completed, (see appendix Eq.(s6) for indicators definition and calculation). It is a measure of the contribution of flexible resource hydro or coal-fired units in participating in power regulation of the energy system. Fig. 10 shows the annual cumulative regulation numbers of coal power and hydropower under non-flexible (base-load) and flexible hydropower mode under HALF scenario in XJ.

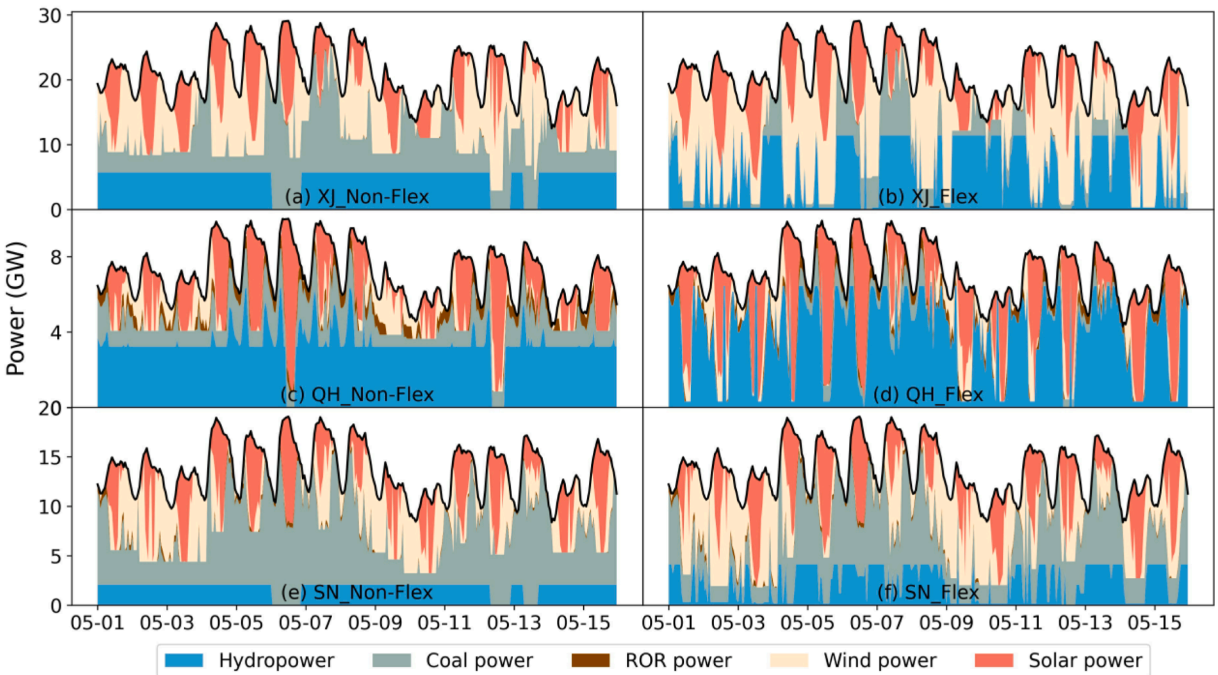


Fig. 9. Power dispatch in non-flexible (base-load) and flexible hydropower operation modes under HALF scenario.

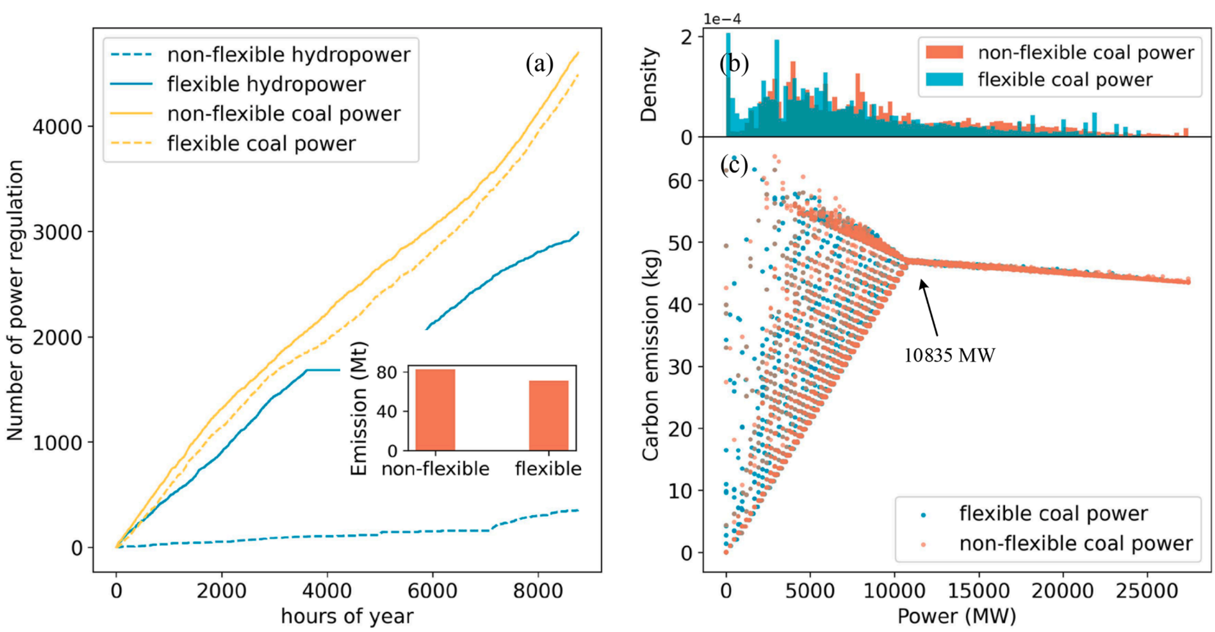


Fig. 10. Cumulative regulation numbers (see appendix Eq.s6) for indicators definition and calculation) in (a) and distribution density of coal power output in (b), and carbon emission characteristics under flexible and non-flexible (base-load) modes in (c). The horizontal axis of the scatter plot is the coal power output, and the vertical axis is the total carbon emissions.

When hydropower shifts from operating in a non-flexible (base-load) mode to a flexible mode, the regulation number of hydropower increases from 352 to 2990. Although the flexible hydropower mode has little effect on the regulation times of coal power, it reduces the emissions by 16.23 %. This can be explained by output distribution density of coal power in Fig. 10(b). When the output exceeds the critical point of 10,835 MW, at which time all coal-fired power units are turned on and running at their lowest, most efficient limit. The coal-fired units operate for 2,659 h in the non-flexible (base-load) hydropower mode, with emission of 44,631 kg. In the flexible mode, they run for 2,100 h, with emissions of 34,914 kg. Below the critical point, coal-fired units run for 6,101 h in non-flexible (base-load) hydro mode, with emissions of 37,914 kg. In the flexible mode, they run for 6,660 h, with emissions of 36,104 kg. The flexible hydropower mode forces coal-fired units to operate more at a lower output state, reducing emissions.

As shown in Fig. 10(c), the critical coal power output point in XJ is 10,835 MW, and varies in QH (830 MW) and SN (7,762 MW). Above these value, total emissions show a linearly decreasing relationship with coal power output (see appendix Fg. s2). This is because all coal-fired units are generating electricity, and the more output, the lower carbon emission intensity. When coal power output is less than threshold, emissions and unit output present a nonlinear relationship due to the

Table 2
Comparison of flexibility indicators for non-flexible (base-load) and flexible hydropower mode.

Indicators	XJ		QH		SN	
	non-flexible	flexible	non-flexible	flexible	non-flexible	flexible
Hydropower proportion	29.41	25.43	58.64	56.34	15.40	13.53
Coal power proportion	34.92	29.51	13.79	7.26	50.54	49.56
Power regulation number	351	2989	3875	4111	469	2584
Wind-solar absorption rate	60.62	76.61	58.7	75.7	80.42	87.12
Loss-of-load (MW)	20089	22321	344100	358708	145030	165472
Coal power fluctuation variance	0.45	0.61	0.10	0.14	0.07	0.09
Carbon emission (*Mt*)	82.55	71.02	10.00	5.52	81.35	79.91

unit opening, closing and ramping operation.

Table 2 shows flexibility indicators of the three provinces for the flexible and non-flexible (base-load) modes. Compared with the non-flexible (base-load) operation mode, the flexible hydropower mode reduces total hydropower output proportion by 3.98 % in XJ, 2.3 % in QH and 1.87 % in SN, respectively. The coal power output proportion has been reduced by 5.41 % in XJ, 6.53 % in QH and 0.98 % in SN, respectively. However, coal power fluctuates to a greater extent and the variance of coal power output increases by 0.152, 0.039 and 0.012. Hydropower flexibility is clearly able to absorb wind-solar energy, with the absorption rate increasing by 15.99 % in XJ, 17 % in QH, and 6.7 % in SN, respectively.

3.3. *Impact of hydro-unit operational range on decarbonization and system flexibility*

These results show the influence of switching from non-flexible (base-load) to flexible hydropower on flexibility and emission indicators. At the unit level, widening the operating range of hydropower units alleviate wind and solar fluctuations and improve power grid flexibility. Here we explore the effect of this flexibility from the perspective of the hydropower units, investigating their operational range and impact on the power balance of energy system at hourly-scale. We selected three flexibility cases: H (operating at 35–100 % of the rated power), M (operating at 50–100 % of the rated power), and L (operating at 65–100 % of the rated power) assuming common Francis hydro units. Table 3 shows the relevant indicators under three cases.

Increasing the operational range of hydro-units does not significantly change the proportion of hydropower and coal power output. The overall energy output mixes do not change greatly, and indicators have not significantly changed. This finding is in contrast with previous findings which have indicated that increasing unit operating range can effectively improve system flexibility [38]. To explain this, Fig. 11(a) gives an indicative figure for how the hydro-unit operational range affects the unit combination at a specific load (350 MW) and Fig. 11(b) further gives the distribution of the cumulative operational range over the total installed hydropower capacity to help illustrate the little difference in flexibility indicators.

Fig. 11 (a) illustrates the load demand achieved by the unit combination under the available operational capacity constraints of the units. The minimum stable output at H, M, and L of a 300 MW hydro-unit is 105 MW, 150 MW, and 195 MW. The load of 350 MW can only be achieved by the combination of two units since the maximum output of one hydro-unit is 300 MW, lower than 350 MW. For H case and M case, the two units can output 175 MW respectively, and for L case, the minimum stable output of the single unit is 195 MW, thus the minimum output of the two combined hydro-units is 390 MW, exceeding the load demand of 350 MW.

The above shows that the H case hydro-unit can match load demands better through the unit combination. Nevertheless, the higher residual load and more hydro-units in the energy system means the operational range of a single hydro-unit will have little influence on the system supply and demand balance. As shown in Fig. 11 (b), the cumulative non-operational ranges for L case are only [0 MW, 195 MW] and [300 MW, 390 MW] through unit combination, which is wider than the M case [0 MW, 150 MW] and H case [0 MW, 105 MW]. The overall energy output mixes and stability indicators do not change greatly as the under all three hydro-units flexibility cases they can meet most of the load demand.

The increase of the hydro-unit operational range does not significantly improve the performance of the indicators, but it may affect the output pattern of the flexible hydropower and coal power resources on the grid. As such we explore the impact of hydro-unit operational range on hydropower and coal power output by examining the cumulative power output variation of hydropower/coal (line chart in Fig. 12) and the difference in hydropower output for different operational ranges (heat map in Fig. 12).

Increasing hydro-unit operational range does not significantly change the curve of coal power's cumulative power output variation (see Fig. 12). However, the trends of cumulative power output variation of hydropower are quite different due to the increase in the operational range of the hydro-unit. Specifically, the cumulative power output variation of hydropower in the lower-range (L) case is the highest in the CURRENT and ZREO scenarios, but for the HALF scenario, the cumulative power output variation is lower than that of the M case and H case. The inflection point in the cumulative power output variation in the

Table 3
Comparison of flexibility indicators for different flexible operating range.

Indicators	Scenarios	XJ			QH			SN		
		H case	M case	L case	H case	M case	L case	H case	M case	L case
Hydropower proportion	CURRENT	11.23	11.24	11.23	44.07	43.88	42.59	4.65	4.67	4.71
	HALF	25.79	25.43	25.62	59.13	56.34	57.09	13.54	13.53	13.60
	ZERO	48.13	48.18	47.69	60.58	59.55	60.26	31.10	31.33	31.82
Coal power proportion	CURRENT	56.05	56.30	56.14	19.41	19.46	19.51	78.48	78.46	78.44
	HALF	29.50	29.51	29.54	7.26	7.26	7.22	49.49	49.56	49.77
	ZERO	0	0	0	0	0	0	0	0	0
Wind-solar absorption rate	CURRENT	0.93	0.93	0.93	0.82	0.83	0.86	0.99	0.99	0.99
	HALF	0.76	0.77	0.76	0.68	0.76	0.71	0.87	0.87	0.86
	ZERO	0.55	0.55	0.55	0.68	0.67	0.65	0.74	0.73	0.73
Coal power output variance	CURRENT	0.09	0.08	0.09	0.08	0.09	0.09	0.01	0.01	0.01
	HALF	0.60	0.61	0.60	0.13	0.14	0.14	0.08	0.09	0.08
	ZERO	0	0	0	0	0	0	0	0	0
Loss-of-load (GW)	CURRENT	4.14	3.74	4.81	35.75	41.49	39.88	0.73	5.14	4.43
	HALF	42.57	22.32	30.23	367.58	358.08	363.62	201.90	165.47	174.59
	ZERO	82925.75	84458.54	84661.86	25681.30	25526.82	24809.21	80123.30	79300.51	79444.06
Carbon emission (*Mt*)	CURRENT	138.82	138.99	138.8	14.18	14.22	14.25	129.92	129.85	129.84
	HALF	70.65	71.02	70.74	5.53	5.52	5.50	79.91	79.91	80.32
	ZERO	0	0	0	0	0	0	0	0	0

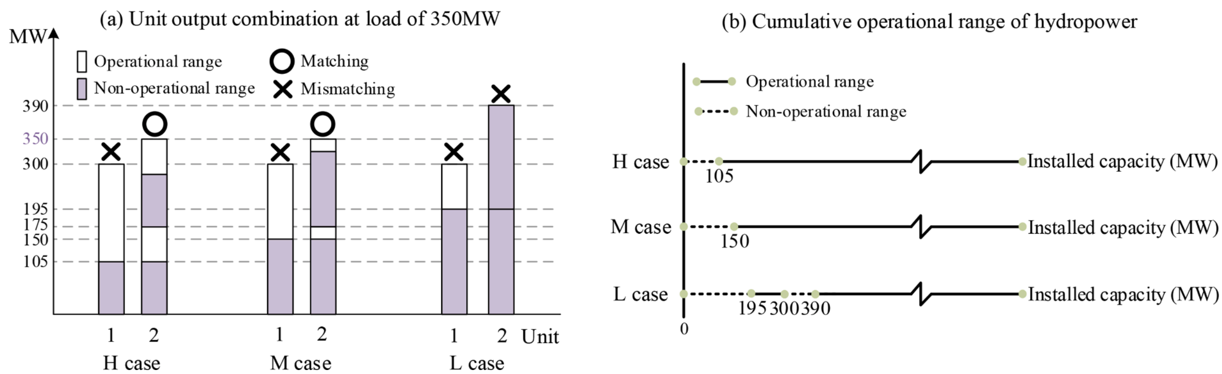


Fig. 11. (a) Unit output combination and (b) cumulative operational range of hydropower under three hydro-unit flexibility cases. The marker circle indicates that the output combination can meet the 350 MW load demand, while the marker cross indicates that it cannot be satisfied.

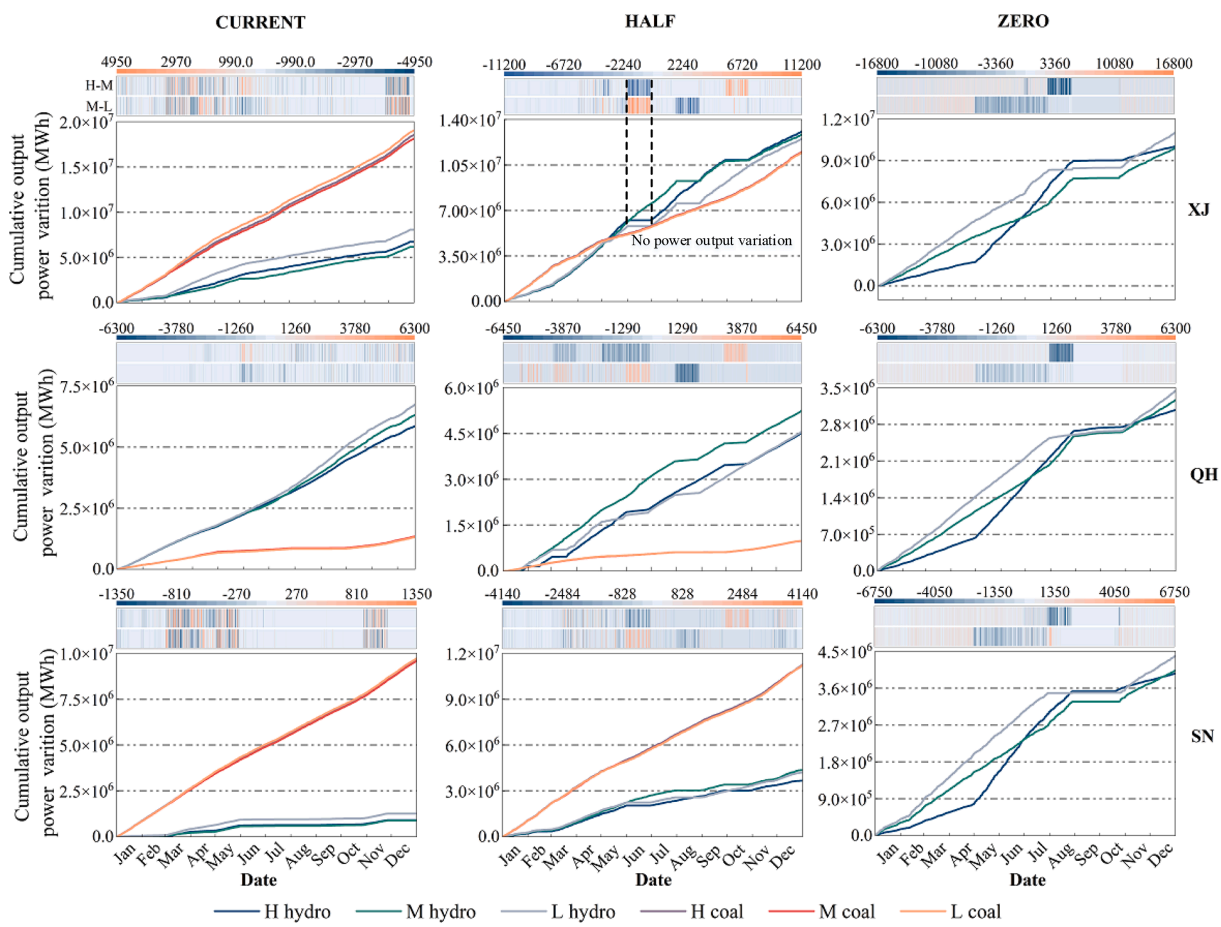


Fig. 12. The output difference of hydropower and the cumulative power output variation under three hydro-unit flexibility cases. The heat map above is the difference in hydropower output for H case minus M case and the heat map below is the difference in hydropower output for M case minus L case.

ZERO scenario L case appeared in July while appeared in August M case and H case. This may be determined by the hydrological inflow and the reservoir operation rules.

From the heat map, the continuous color blocks from CURRENT to HALF to ZERO have a wider distribution showing that when the installed capacity of coal power decreases, hydropower needs to continuously output at maximum power to share the base-load task lost by the coal plant. For example, in June in XJ HALF scenario, the hydropower in H case and L case maintains full load output, with almost no power regulation. Correspondingly, the cumulative power output variation remains flat.

4. Conclusion

Here we investigate the hydropower flexibility needed to reduce carbon emissions and replace coal power during a coal phase-out across three provinces. We include the relationship between generator output and carbon emissions under transient-operation as generators respond rapidly to varying solar and wind output. We constrain the model to annual reservoir scheduling. We investigate three different energy scenarios for the coal phase-out process (CURRENT, HALF, and ZERO) for both the non-flexible and flexible operation of hydropower resources and derive carbon emissions along with system flexibility indicators. We find that the common assumption of a constant emission coefficient in this case underestimates emissions by as much as 8.5 % in XJ, 3.4 % in QH, and 11.1 % in SN. With coal power capacity halved, an interesting exception is for SN where coal power plants in transient-operation (start-up, ramp up, ramp down, and shutdown) emits a greater amount in the HALF with 5.228Mt than the CURRENT scenario with 4.274Mt. This is due to the wind-solar volatility in the HALF scenario resulting in greater power output variation of coal-fired power, which in turn results in more emissions. Coal phase-out worsens flexibility indicators and the duration and total amount of loss-of-load in the ZERO scenario is much higher than in the other scenarios. Comparing flexible and non-flexible (base-load) operating modes for hydropower, we find that flexible hydropower can reduce wind-solar curtailment and emissions significantly. For example, in HALF scenario for XJ, flexible hydropower has little effect on the regulation times of coal power but it reduces emissions by 16.23 %.

The effects of unit-level flexibility parameters on carbon emissions and system flexibility indicators are analyzed and We find that increasing the operational range of hydro-units does not improve the flexibility indicators, because even hydro-units with low operational range can effectively alleviate the mismatch between supply and demand through unit combinations.

5. Discussion

Some literatures also use the Dispa-set model to study the transformation of energy systems typically characterized by the decommissioning of coal power and the increase of wind and solar power [19,39]. It is worth pointing out that these literatures focus on water-energy nexus, emphasizing the interaction between the availability of water resources and the power system (water for hydropower generation and cooling water for thermal power). However, this paper only focuses on the interaction between hydropower and coal power in the power system to provide generation flexibility. Similar to the results of this paper, that is, hydropower will be more frequently used as the purpose of balancing demand rather than base load power generation in the transformation of hydro-coal energy system. However, these literatures still used the constant emission coefficient of coal power units when evaluating the carbon emission characteristics during the transformation. The results of this paper confirm that such a constant emission coefficient will overestimate the effect of carbon emissions, leading to inappropriate policy formulation. On the other hand, these literatures use the soft-linking method to combine Dispa-set with the hydrological model LISFLOOD and the capacity expansion model TEMBA, etc., which can provide more reliable information for the decarbonization transformation of the power system and capture the technical characteristics of hydropower and coal-fired power units.

One limitation in this paper is the model representation of unit-level flexibility. In practice, structural characteristics of hydro turbines result in different conditions for different water heads. Under certain conditions hydro turbine operation can enter a damaging vibration mode which is usually avoided in operation [40]. As such, the flexible range of the unit is discontinuous and dependent on a changing water head. We speculate that the consideration of the vibration zone will change the results of unit commitment of hydropower and further affect the overall available flexible capacity. Future work could investigate the magnitude of these impacts.

CRediT authorship contribution statement

Ziwen Zhao: Conceptualization, Methodology, Software, Investigation, Writing – original draft. **Xinjun Ding:** Resources, Writing – review & editing. **Paul Behrens:** Resources, Writing – review & editing. **Jianling Li:** Resources, Writing – review & editing. **Mengjiao He:** Visualization. **Yuanqiang Gao:** Visualization. **Gongcheng Liu:** Visualization. **Beibei Xu:** . **Diyi Chen:** Writing – review & editing.

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.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.apenergy.2023.120684.

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