The persistence of flexible coal in a deeply decarbonizing energy system

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Abstract

Extensive literature has highlighted the difficulty in operating baseload power plants—especially coal-fired units—in a decarbonized electric power system with a high share of variable renewable energy, with some of it recommending immediate coal phaseouts. However, the coal fleet across China is large and young, making its imminent phaseout unrealistic. Moreover, power system operators and policy makers face other constraints in their pursuit of energy system decarbonization—chief among them the need to achieve high levels of reliability—something coal units could provide. We assess the persistence of coal in a decarbonizing power system under various retrofit scenarios that seek to enhance the flexibility of coal units: after all, energy transitions do not occur in a vacuum and owners of coal power plants will likely pursue innovations to extend the lifetimes and profits of their assets, even as the wider energy transition unfolds. We evaluate the economic and environmental impacts of improving coal power unit flexibility in Jiangsu’s power system under four levels of renewable energy penetration and three scopes of coal flexibility retrofits. Our results show that coal units persist even at very high renewable penetrations, and retrofits help them reduce power system costs, enable renewable energy integration, and marginally cut emissions. Smaller coal units become peaker rather than baseload units, providing the power system with flexibility rather than just energy. Our results show how challenging the low-carbon transition is likely to be without outright phaseouts of coal generation.

1. Introduction

Averting the worst consequences of climate change requires the decarbonization of the global energy system over the course of this century [1, 2]. Although various deep decarbonization pathways have been proposed, there is broad consensus among them that the unmitigated release of carbon pollution from coal power plants needs to be eliminated [3, 4]. Studies accomplish this either through a global phase-out of electric power production from fossil-fueled power plants or the deployment of carbon capture and storage (CCS) systems on these facilities [5, 6].

The vision of a fossil phase-out, while crucial for sustainable energy futures, clashes with realities that are especially evident in China—the world’s largest coal consumer and CO₂ emitter [7, 8]. China has pledged to ensure that its carbon emissions peak before 2030 and wants to achieve carbon neutrality before 2060 [9]. These are ambitious national greenhouse gas (GHG) emission reduction goals, but the policies used to achieve these goals are pursued with different levels of commitment. For example, China has aggressive variable renewable energy (VRE) development targets [10], but its coal power development policy has been rather vacillating.
This betrays the government's recognition of the many stark constraints facing its electric power system, which include increasing demand; the variability and intermittency of VRE production; the need for firm but flexible electric power generation; the importance of power system reliability; the air pollution impacts of coal; and, of course, the need to mitigate GHG emissions. For example, since 2005, China has phased out small coal-fired power units but installed many more large and advanced facilities [11]; these new power units—more efficient than smaller units in both energy and environmental performance—are destined to remain in operation beyond 2040 [12].

Given the technical, economic, financial, social, and political constraints facing a rapid and complete phase-out, coal will likely remain an indispensable source of energy in China for at least the next several decades, shaping China's long-term energy transition in the process [13]. Existing studies have explored visions for eliminating coal from the Chinese energy system [14–16]; these often focus on the rapid and deep penetration of VRE sources [17]. However, these studies do not provide credible pathways for implementation, since they focus on emission reductions while ignoring four powerful engineering-economic forces that will drive this power system transition. First is the economic performance of the power system as a whole, which needs to minimize the cost of service delivery while achieving high operational reliability [18–20]. Compared with natural gas, coal power is and will remain (at least in the near future) reliable and affordable in China. Unlike natural gas, China is highly self-sufficient in this resource. As a result, it is a country where coal prices and carbon prices are low; its supply secure and proximate. Second are variations in technical performance across coal-fired power units, including heat rates and ramping constraints. Studies often overlook or coarsely characterize the granular details of power system operations, given the complexity of the electric grid [21–25]. We do not need to look further back than this winter's experience in Texas [26] to see the extent to which overlooking the operational constraints that face the grid would risk power system reliability and yield potentially disastrous consequences. With rising VRE shares, the risk of miscalculation could grow, too, which is why aggressive VRE penetration targets highlight the significance of characterizing the detailed operations of future power systems. Third is the longevity of large energy infrastructure like coal power plants—especially those built recently—and thus the path dependency of (or infrastructure lock-in associated with) any decarbonization effort in China [27]. This longevity influences not only the financial decisions made by asset owners, but also the policy decisions that are made by government as it navigates the energy transition, including decisions to rescue or abandon infrastructure [28, 29]. Fourth and finally, energy transitions do not occur in a vacuum: owners of coal power plants will likely pursue innovations in how they operate their plants to extend their lifetimes and profits (especially considering that China's coal units are new and efficient), even as low-carbon development proceeds apace. One way of doing this is to improve their flexibility through retrofits [26]. There are other technologies that could also provide essential flexibility to accommodate electricity generated from intermittent renewable sources—these include batteries, flywheels, pumped hydro, and even stored hydrogen. Some of these will remain more expensive in the foreseeable future than the coal retrofit cost estimates that we consider here. Others, like pumped hydro, might face physical or socio-political constraints that limit their adoption.

Here, we analyze the technical, economic, and emissions implications of deploying China's coal-fired power units as a source of firm, flexible electricity to complement that generated through VRE sources. Assessments of methods to improve the flexibility of coal-fired power units generally focus on the facility itself, stopping at the plant boundary and ignoring the system-wide implications of improved flexibility [30–32]. These studies have assessed the cost uncertainties associated with coal power plant retrofits that enhance flexibility. Our novel contribution is to quantitatively and comprehensively assess the persistence of coal in a decarbonizing power system under various retrofit scenarios that seek to enhance the flexibility of coal power plants. In doing so, we answer challenging questions for energy systems like China's which have a deep commitment to coal through the medium-term.

We simulate the hourly operations of the power system in the Chinese province of Jiangsu. We focus on Jiangsu because it is responsible for the second largest electricity consumption among China's provinces: it serves more than 80 million people, has an aggregate demand of more than 600 TWh, and a peak load of approximately 100 GW in 2019 [33]. More importantly, it has a large installed capacity of coal-fired power plants (more than 60% of all capacity), limited ability to expand flexible hydropower capacity, and aggressive VRE development goals that center on the installation of onshore and offshore wind power plants—the province is especially rich in wind resources [34].

We conduct this simulation under four different levels of VRE penetration, ranging from 2018's installed capacity of 22 GW to 50 GW, 100 GW, and 150 GW—figures that are consistent with Jiangsu's plans and plausible given its rich resource base [35–37]. We also consider three different retrofit scenarios that improve the flexibility of different classes of coal power units. The first of these sees flexibility retrofits implemented at all coal-fired power units with an installed capacity less than 600 MW. The
second scenario extends these retrofits to all coal-fired power units with an installed capacity less than 1000 MW. The third and final scenario extends retrofits to all coal units.

The simulation employs a day-ahead unit commitment (DA-UC) and real-time economic dispatch (RT-ED) model. Compared with coarser energy system analyses, this research provides a granular simulation of power system operations and enables a better understanding of the interplay between enhanced flexibility in coal-fired power units and VRE penetration. Our approach allows us to compare the system benefits of enhanced coal power plant flexibility—as manifested in reduced power system costs—with the cost of those flexibility retrofits, providing estimates of the benefit-to-cost ratio (BCR) of retrofitting coal units at the level of the individual units. Furthermore, this approach reveals the extent to which coal flexibility improvements can allow coal power units to complement VRE production and at what cost (profit or loss) to the units themselves. System-wide benefits of coal flexibility improvements are in the public’s interest, whereas the performance and profits of coal units is the concern of private interests. Understanding the system-wide benefits and the costs to individual units not only yields implications regarding electricity market design, but also allows government to prioritize coal power unit retrofits. In summary, our research allows stakeholders to design better policy instruments that target different classes of coal units in the medium-to-long term.

2. Method and scenarios

2.1. Production cost optimization model

A production cost optimization model, which is comprised of a DA-UC model and a RT-ED model, is used to simulate the hourly operations of the power system’s electric generating units, representing their unique economic, technical, and environmental attributes. The model minimizes the total power supply system costs subject to economic, technical, operational, and regulatory constraints of power system operations. The DA-UC model prescribes the power generation and reserves of all power generating units for each of the next 48 h, which includes the next day’s 24 h plus an additional 24 h. This is consistent with the goal of meeting the expected demand—as estimated for the day ahead—at minimum cost. The demand and renewable power generation estimates are then updated to their realized values in real time, and the RT-ED model is run to find the optimal hourly dispatch of all generating units, considering that their commitment and operational status is as prescribed in the day-ahead by the DA-UC. The relative MIP gap tolerance of the DA-UC model, which is a mixed integer linear program, is set to 0.01%. Please refer to the SI, S1 (available online at stacks.iop.org/ERL/16/064043/mmedia) for more details on the model, inputs and outputs.

2.2. Coal flexibility retrofits at different VRE penetration scenarios

We design plausible scenarios that represent various combinations of coal power flexibility and renewable energy futures. The scenarios are summarized in Table 1. Please refer to the SI, S2 for more details of the power system in Jiangsu under different scenarios. Improved coal power flexibility would imbue upon these generators lower minimum power generation, higher ramping capability, and lower minimum up and down times. This strategy has been proposed previously [31] as a way of making coal units operationally comparable with natural gas combined cycle units in terms of flexibility. Operating coal flexibly adversely affects its technical and environmental performance. Our data show that if all coal units operated at full capacity, the fleet-averaged CO₂ emissions rate would be approximately 830 kg MWh⁻¹; this number would increase to approximately 890 kg MWh⁻¹ if units operated at 50% capacity factor—a 7% increase.

2.3. Cost-benefit analysis (CBA)

We estimate the benefit-to-cost ratio (BCR) to better understand the significance of retrofits for improving coal power flexibility. The benefit here refers to the cost reduction in power system operations from coal flexibility improvements, while the cost refers to the capital cost of the retrofits. We note that the benefit here is a clear underestimate; improving coal power flexibility generates additional benefits that we do not consider. For example, it avoids installation of other flexible resources (e.g. energy storage systems), avoids renewable curtailment and enables more renewable integration. Monetizing these benefits is out of scope of this research and hence left out of the CBA.

The annual system benefit is calculated by comparing the power system costs before and after coal power flexibility improvements; these are derived from the production cost optimization model. The annual cost is represented by the annualized capital cost, and it is calculated from the total capital cost and the fixed charge factor (which is also known as the levelizing factor). The BCR is as follows:

\[
\text{BCR} = \frac{\text{ASB}}{\text{ACC}},
\]

and

\[
\text{ACC} = \text{TCC} \times \text{FCF} = \text{NC} \times \text{CC}_{\text{perCap}} \times \frac{r \times (1 + r)^Y}{(1 + r)^T - 1}
\]

where NC is the nameplate capacity of retrofitted coal power in MW; CC_{perCap} is the capital cost per
installed capacity in RMB MW$^{-1}$; $r$ is the discount rate, $r = 7\%$; $Y$ is the lifetime of retrofitted coal power. Given the capital cost ranges of improving coal power flexibility [38], we assume $CC_{\text{perCap}} = 36000$ and $Y = 30$ for the upper bound calculation of BCR, and $CC_{\text{perCap}} = 200000$ and $Y = 20$ for the lower bound calculation.

### 2.4. Economic performance of coal units

We use the economic penalty to reflect the economic performance degradation of a unit. The economic penalty of unit $u$ ($EP_{u}$) equals the change of economic costs ($Cost_{u}$) divided by aggregate power generation ($E_{u}$). Such average cost reflects how a unit is operated and utilized, such as the number of startups, the duration of operation, and the power output away from full capacity when committed. A unit that constantly and steadily operates at its full capacity has better economic performance, because this operation avoids startup costs; in addition, no-load costs are diluted into more power generation. A unit with frequent startups and power output far removed from full capacity when committed has lower economic performance. Cost of unit $u$ ($Cost_{u}$) includes three parts: incremental marginal cost ($C_{M,u}$), startup cost ($C_{SU,u}$), and no-load cost ($C_{NL,u}$):

$$EP_{u} = \Delta \frac{Cost_{u}}{E_{u}} = \Delta \frac{C_{M,u} + C_{SU,u} + C_{NL,u}}{E_{u}}.$$

$E_{u}$, $C_{M,u}$, $C_{SU,u}$, and $C_{NL,u}$ are derived from the production cost optimization model.

### 2.5. Coal unit profits

Profits from a coal unit equal revenue minus cost. Revenues of unit $u$ ($Revenue_{u}$) equal the product of electricity price ($P$) and aggregate electric power generation ($E_{u}$):

$$Revenue_{u} = P \times E_{u}.$$

Costs ($Cost_{u}$) of unit $u$ consist of: incremental marginal cost ($C_{M,u}$), startup cost ($C_{SU,u}$), and no-load cost ($C_{NL,u}$):

$$Cost_{u} = C_{M,u} + C_{SU,u} + C_{NL,u}.$$

Profits from unit $u$ ($Profit_{u}$) equals the revenue minus cost:

$$Profit_{u} = Revenue_{u} - Cost_{u} = P \times E_{u} - (C_{M,u} + C_{SU,u} + C_{NL,u}),$$

where $P = 391$ RMB/MWh, which is the benchmark electricity price of Jiangsu’s coal units [39].

### 3. Results and discussion

#### 3.1. Flexible coal reduces power system costs and alters dispatch in high VRE scenarios

Our results show that implementing retrofits at coal power units that improve their flexibility yields substantial benefits that will likely make these units persist, even as the wider low-carbon transition unfolds. These benefits are shown in figure 1. Retrofits reduce total power system costs, especially in scenarios with high VRE penetration (figure 1(A)); we also estimate the marginal benefits of flexibility retrofits, which is the total cost reduction divided by the retrofitted capacity (figure 1(B)). Moreover, the BCR of flexibility retrofits often exceeds 1 (figure 1(C)), and uniformly exceeds 1 in high VRE penetration scenarios; in fact, across power units, the BCR ranges from 2 to 22 when the installed VRE capacity is 150 GW. Across different classes of coal power units, retrofitting smaller units generates larger BCR.

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Table 1. Range of VRE expansion, demand, and coal flexibility scenarios developed for this analysis.

| No. | Renewable capacity | Other power supply infrastructure | Power demand | Coal flexibility$^a$ |
|-----|--------------------|-----------------------------------|--------------|----------------------|
| 1   | As in 2018 (22 GW) | As in 2018                         |              | Business as usual (BAU) |
| 2   | 50 GW              | Remain the same as it was in the beginning of 2020 | 750 TWh      | Improved flexibility <600 MW |
| 3   | 100 GW             | BAU                                | 920 TWh      | Improved flexibility <600 MW |
| 4   | 150 GW             | BAU                                | 1065 TWh     | Improved flexibility <600 MW |

$^a$ BAU flexibility parameter: minimum generation 50% of nameplate capacity; ramp up/down capability: 60% of nameplate capacity per hour; startup/shutdown ramping capability: 100% of nameplate capacity per hour; minimum down time: 8 h; minimum up time: 10 h.

Improved flexibility parameters [30–32]: minimum generation 30% of nameplate capacity; ramp up/down capability: 100% of nameplate capacity per hour; startup/shutdown ramping capability: 100% of nameplate capacity per hour; minimum down time: 5 h; minimum up time: 6 h.

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Figure 1. Reduction in power system costs from implementing flexibility retrofits at coal power units, relative to a system without such retrofits. (A) Total cost reduction, which becomes more significant at higher VRE penetrations. (B) Cost reduction adjusted for capacity; as the scope of the flexibility retrofits expands to larger coal units, the marginal benefits decline. (C) BCR ranges for coal flexibility retrofits; when VRE capacity reaches 150 GW, improving coal flexibility yields far more benefits than costs.

The first of these results—that improving coal power flexibility reduces total power system costs—is expected, because a more flexible system could handle ramping events more easily and cheaply (start-up costs being high for thermal power units). Higher VRE penetrations in the system necessitate more ramping events, amplifying the cost reductions associated with flexibility retrofits. Moreover, the relationship is non-linear, as shown in figure 1(A). When installed VRE capacity increases from 100 GW to 150 GW, the total reduction in power system costs that is derived from flexibility retrofits jumps from less than 500 million RMB to more than 1 billion RMB when only small coal units (<600 MW) are retrofitted. In the scenario where all coal units are retrofitted, the cost reduction is 2.5 billion RMB. The benefits in the transition from 100 GW to 150 GW are much larger than those associated with the shift from 50 GW to 100 GW of installed VRE capacity, underscoring the significance of flexibility retrofits across the baseload fleet in high renewable energy futures.

Our modeling approach allows us to elaborate the determinants of total power system cost reduction by looking at how power is dispatched in detail. Specifically, we find that the major determinants of cost reduction are threefold, and each of these speaks to ongoing tensions within or between technological clusters that are competing to decarbonize the energy system. The first source of cost reductions is that flexibility retrofits enable the deeper integration of electricity produced from VRE sources by avoiding their curtailment: the marginal cost of this electricity is near-zero. One large challenge in deeply decarbonizing the power system is better understanding how to manage the integration of large amounts of electricity from VRE sources while maintaining the reliability of the power system and controlling service costs, and our analysis shows that implementing retrofits at coal power units to improve their
flexibility is a plausible pathway. The second source of cost reductions speaks to the emerging battle between firm, flexible electricity generation technologies. In the U.S., natural gas has supplanted coal as the largest single component of the electricity generation mix. In our case, improving the flexibility of coal power units enables the substitution of cheap, reliable coal for expensive natural gas—the reverse of the American experience. The third and final source of cost reductions speaks to the conflict within coal itself: improving the flexibility of coal units allows more efficient, larger coal power units to provide more electricity by operating at or near full capacity, reducing their overall costs. On the other hand, smaller coal power units provide more flexibility but less electricity.

In terms of the marginal benefits of flexibility retrofits, under all scenarios the marginal benefits are highest if only smaller coal units with a capacity of less than 600 MW are retrofitted. As the scope of retrofit expands, the marginal benefits decrease (Figure 1(B)). This result provides power system operators and policy makers with evidence to propose and defend phased approaches to a fleetwide retrofit, or to devise targeted policies for each class of power unit. Finally, the BCR of flexibility retrofits is uniformly higher than 1 (i.e. the system-wide benefits exceed retrofit costs) in the case where installed VRE capacity is highest at 150 GW. Much like the trend with marginal benefit described above, the BCR is highest if only coal power units with capacities smaller than 600 MW are retrofitted, decreasing as the scope of the retrofit expands.

We note that we consider the most conservative case here, and that the benefits of flexibility retrofits in the real world are likely greater than what we report. For example, in calculating the lower bound of BCR we take the retrofit cost to be 200 000 RMB MW$^{-1}$, the upper bound of estimates [38]. More importantly, we only assess the operational value of the flexibility retrofit to the system but do not consider its capacity value. Improving the flexibility of coal power units
reduces VRE curtailment and preempts the installation of other flexible resources that enable VRE integration—such as energy storage, which means that the economic benefit and BCR of improved coal flexibility would be higher once capacity value is incorporated.

Implementing flexibility retrofits also affects hourly marginal costs. Section S3 in the SI provides a summary of hourly marginal costs under various scenarios.

3.2. Flexible coal allows power system decarbonization
Improved coal flexibility could plausibly claim to accomplish three major environmental objectives in the power system. These are: (a) reducing curtailment and enabling integration of more electricity production from VRE sources; (b) reducing fossil fuel consumption; and (c) mitigating GHG emissions from the electric power sector.

First, a key challenge to VRE development is electricity curtailment; one cause of this curtailment (among many) is the lack of power system flexibility. Our results show the degree to which improving the flexibility of coal units increases VRE integration (figure 2). The benefits are negligible until installed VRE capacity reaches 100 GW. At that level, flexibility retrofits to coal power units enable the integration of more than 500 GWh of renewable electricity that would have otherwise been curtailed. As the scope of the retrofits expands beyond smaller units, these benefits are amplified. At an installed VRE capacity of 150 GW, the reduction in curtailment leaps to more than 2 TWh and the influence of different retrofit scopes becomes evident: while retrofitting only smaller coal units leads to a 2 TWh reduction in curtailment, retrofitting all coal plans leads to a 6.6 TWh reduction in VRE curtailment. This may account for 2% of total VRE generation, but it constitutes an 82% reduction in electricity curtailment compared to the no-retrofit scenario.

Increasing the flexibility of coal power units also reduces fossil fuel consumption and CO₂ emissions from the power system. Figure 3(A) shows that more
CO₂ emissions are mitigated as the scope of flexibility retrofits expands from just the smaller coal units (<600 MW) to include larger ones (<1000 MW) and finally all coal units. As installed VRE capacity expands, flexibility retrofits amplify CO₂ emissions mitigations, too. These results emphasize the complementary nature of coal flexibility and VRE deployment, with the surge in installed renewable capacity to 150 GW reducing emissions by up to 4.5 million tonnes of CO₂, which constitutes an admittedly marginal 1.25% of Jiangsu’s emissions.

This result seems counter-intuitive: how does improving coal flexibility, which enhances its market competitiveness with natural gas power plants and leads to the latter’s substitution, reduce fossil fuel consumption and CO₂ emissions? It comes down to the sheer dominance of coal in Jiangsu’s power system, from which follows that the implementation of coal flexibility retrofits across the province enables reductions in the curtailment of VRE sources and increases power generation from large coal units with superior energy and environmental performance. By shouldering the burden of providing flexibility to the power system, small coal power units are also producing less power—this is good for emissions given their poorer environmental performance (figure 3(C)). This result underscores the fact that improving coal flexibility is consistent with decarbonizing the power system—at least in the near-term until these units achieve plausible retirement ages.

3.3. Substituting energy for flexibility in small coal-fired power units

How can we convince coal-fired power units to substitute energy for flexibility in pursuit of broader societal aims? In figure 4, we provide box and whisker plots that present the range of effects among different classes of coal units once coal flexibility retrofits are implemented. Figure 4(A) shows the change in power generation, from which the impact of coal flexibility retrofits on coal unit revenues can be estimated: increased power generation yields additional
revenues. Figure 4(B) shows the economic penalty incurred by different coal units. Here, we define the economic penalty as the degradation in the economic performance of a unit; economic performance is the total economic cost of operating each unit divided by the total electricity it generates. Figure 4(C) explicitly presents the change in each unit’s annual profit, which is revenue minus cost.

Figures 4(A) and (B) show that smaller coal units—those with installed capacities less than 600 MW—have lower power generation and worse economic performance from improved coal flexibility. However, larger coal units—those with installed capacities greater than 1000 MW—have higher power generation and better economic performance. These trends are consistent across scenarios. In other words, affording smaller coal units greater flexibility enables them to satisfy the needs of power system, given their smaller minimum output and cheaper startup and shutdown. This increases their costs and reduces their capacity factors. Large units remain online and operate at levels closer to their full capacities. Smaller coal units see their role transformed from baseload units—which is the case today—to peakers, while the role of larger coal power units as baseload units is further entrenched.

This transformation comes at a cost: smaller coal units face dramatic cost increases in their new role. In fact, figure 4(C) shows that smaller coal-fired power units face profit losses regardless of the scope of the coal flexibility retrofit and VRE penetration. Flexibility retrofits reduce power generation from these small units, diminishing their economic performance in the process. Larger coal power units see their profits increase regardless of the scope of the coal flexibility retrofit and VRE penetration. The effect on the in-between group depends on retrofit scope and VRE penetration.

Our results underscore how increasing VRE capacity always applies economic pressure on small coal-fired power units, shrinking their profits. Expanding the scope of the retrofit rewards larger coal-fired power units and applies further pressure on smaller ones. Studies have demonstrated the first of these pressures: increasing VRE capacity squeezes the profits of baseload fossil fuel generators. Our first contribution is to highlight how coal flexibility retrofits will further squeeze those profits. Our second contribution is to show how flexibility retrofits, while detrimental to generator profits, are complementary to the power system’s wider economic and environmental aims. These competing pressures make the establishment and careful management of an ancillary services market—one that rewards flexibility rather than just energy—an imperative to plausible decarbonization of the Chinese power system. Establishing a robust ancillary services market in Jiangsu would offer a market-based mechanism for securing flexibility. This will happen as China slowly but surely transitions to a market-based power system. Jiangsu itself is also encouraging the development of an ancillary services market to prepare for higher penetrations of VRE. Detailed results regarding each specific coal unit’s power generation, environmental performance, and profit can be found in the supplementary information (SI), S4–S7.

3.4. Discussion

Results clearly show that improving coal power flexibility brings multiple benefits for power systems with high levels of VRE penetration. The benefits include reductions in power system costs and electricity curtailment from VRE sources, as well as lower GHG emissions. Other sources of flexibility might be preferred to coal; we discuss a few here. First, there is natural gas, which is extremely flexible. In areas of the world where natural gas is more expensive or security of supply more precarious, the decision between coal and natural gas will come down to strategic hedges against current and future commodity prices. In this case, coal power remains cheaper than natural gas power even when carbon price reaches 300 RMB per tonne of CO₂ [40], which is a price far higher than the price in China’s current carbon emissions trading system. There is a range of technologies that could give the power grid flexibility (and other benefits); these include energy storage systems (batteries of all kinds), flywheels, pumped hydro storage, and eventually hydrogen. Energy storage is currently more expensive than coal flexibility retrofits and will likely remain so in the future [41, 42]. Pumped hydro storage often (but not always) requires large-scale development of new infrastructure; it is also physically constrained. All technologies for hydrogen production, transportation, and storage (except today’s dominant steam methane reforming) would be more expensive than coal flexibility retrofit—they also entail the deployment of new infrastructure, which can be socio-politically constrained [43, 44]. In addition to flexibility, storage offers other benefits to the system—some of which cannot be readily compared to coal power plants, making direct comparisons between the two inexact.

There are uncertainties surrounding future coal power development in China—new coal power may be constructed and existing coal power may be phased out, and hence coal power capacity may increase or decrease. These uncertainties would also affect the benefits from improving coal power flexibility. This paper makes the problem tractable by assuming the power generation capacity (including coal power) as given in 2018 with various expansion scenarios of VRE. This assumption helps us focus on the effects of coal flexibility. Nonetheless, it is inevitable that coal power capacity will gradually decrease as
China’s climate policies become more ambitious, new low-carbon technologies are deployed, and coal power plants retire. This would make flexibility even scarcer than it is in the scenarios this research envisions. In this regard, our estimation of system-wide benefits from flexible coal should be viewed as a conservative, lower-bound estimate; real benefits could be even higher and the role of coal flexibility retrofits could be more important.

Regardless, assuming no radical changes to the power system beyond mass VRE penetration, coal flexibility retrofits cannot significantly reduce CO₂ emissions. Our results show that flexibility retrofits alone achieve 2% reductions in power system emissions: it is important to recognize that this is not a sufficient strategy for decarbonization. To achieve decarbonization targets that can help stabilize the climate, coal will have to be phased out in China through aggressive climate mitigation measures, such as carbon pricing. Another possible option is to equip these flexible coal units with CCS systems. Some researchers argue that fossil CCS is crucial to deep decarbonization, especially if we exclude others like nuclear; others argue that fossil CCS is costly, that its record of deployment has not been successful (to put it mildly), and that it extends our dependence on unsustainable resources. Fitting CCS to coal units would cost more upfront than a flexibility retrofit and incur an energy penalty of approximately 10% [45, 46], increasing costs. However, it also gets us much closer to our low-carbon goals. Fundamentally, the choice to deploy CCS will depend on the evolution of China’s climate ambitions, alternative low-carbon technologies, and wider energy security, though it is an important question that we plan to explore.

This research looks at the 2018 generation fleet, modified assuming various VRE expansion scenarios, but it provides clear implications regarding the risks and benefits of flexible coal in a decarbonizing energy system. Making coal plants flexible might seem counterproductive, locking the system into a coal-dependent pathway, but in the short term and in the absence of other competitive alternatives it could enable further decarbonization down the road. First, improving coal power flexibility avoids stranded assets which may increase political resistance to low-carbon investments broadly and is inefficient regardless. It also keeps a very strong constituency—coal unit operators—somewhat satisfied. Second, flexibility retrofits to coal power units enable the integration of renewable electricity that would have otherwise been curtailed and hence increase profits of VRE, eventually promoting and accelerating the penetration of VRE. Third, improving coal power flexibility does not impede the development of other flexible generation eventually; it just acts as a bridge to the deployment of other technologies in the future, and it helps power system operators gain experience with the integration of vast amounts of VRE in the grid. Finally, implementing retrofits at some coal units to improve their flexibility is a plausible pathway to speeding up the process of coal power phaseout among coal generators that cannot make an economic case in this radically new techno-economic context where flexibility is important.

4. Conclusion

The coal power fleet across China is large and young, making its imminent phase-out unrealistic. Moreover, power system operators and policy makers face many, diverse constraints in their pursuit of energy system decarbonization strategies. This study evaluates the persistence of coal even as the wider energy transition unfolds in Jiangsu Province. Our results show that flexible coal units could help the power system achieve multiple economic and environmental benefits simultaneously, especially at high levels of VRE penetration; these benefits include a reduction in electricity curtailment from VRE sources and lower GHG emissions. These retrofits also reduce power system costs. These flexible units could play a role in bridging Jiangsu’s transition to a low-carbon future—one that does not risk stranding billions of dollars in assets and causing severe socio-economic disruption.

The purpose of this investigation is not to ‘lock’ the power system into a coal-dependent pathway. Indeed, there are myriad technologies that can be used to achieve flexibility and could advance decarbonization goals. Improving coal power flexibility would constitute an effort to help maintain the reliability of the power system in the short term, even as it vastly expands renewables, until new, better, low-carbon technologies are deployed in the coming decades. This provides a bridge that fully exploits existing capacity until those better technologies—which can also provide flexibility and complement renewables—are deployed.

Improving coal power flexibility alone has limited effects in reducing power system emissions. If Jiangsu truly wishes to achieve deep decarbonization over the medium to long-term, it must treat these retrofits as a steppingstone to greater emissions reductions. Otherwise, cumulative GHG emissions from Jiangsu alone would deplete a large share of global remaining carbon budget for the ‘well below 2 °C’ target enshrined in international accords. A possible way to achieve these with coal power is through CCS. Alternatively, this strategy only delays a zero-coal pathway until other flexible energy technologies become more mature, and in the meantime gives power system operators valuable experience in grid integration of large levels of VRE generation. In the long run, storage deployment, demand side response, and an interconnected robust regional power grid are all
essential measures to enhance the integration of VRE generation.

One prominent stumbling block to implementing coal flexibility retrofits is the severe profit decrease that small coal-fired power units (which should much of the burden for providing flexibility) will experience; another is the high capital cost of flexibility retrofits. This dilemma between public and private interests will require targeted economic incentives for smaller coal units to encourage flexibility retrofits as well as innovations in the design of electricity markets, such as rewarding coal power units for their flexibility rather than just their energy by developing an ancillary services market. Our results provide useful rules of thumb regarding the role that could be expected of flexible coal for both power system operators and policy makers who are keen on managing an energy transition that could prove highly disruptive.

Data availability
The data that support the findings of this study are available upon reasonable request from the authors.

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Author contributions
All authors conceived the research. M L and Y D designed the study. S G and Y D collected and processed the data. M L developed the energy model and conducted the system operational simulations. M L, A A and R S wrote the paper and drew the figures. All authors discussed the results and commented on the manuscript.

Conflict of interest
The authors confirm that there are no known conflicts of interest associated with this article. The authors have no competing interests as defined by the Publishing Group, or other interests that might be perceived to influence the results and/or discussion reported in this paper.

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References
[1] Meckling J, Sterner T and Wagner G 2017 Policy sequencing toward decarbonization Nat. Energy 2 918–22
[2] Waisman H et al 2019 A pathway design framework for national low greenhouse gas emission development strategies Nat. Clim. Change 9 261–8
[3] He G, Lin J, Zhang Y, Zhang W, Larangeira G, Zhang C, Peng W, Liu M and Yang F 2020 Enabling a rapid and just transition away from coal in China One Earth 3 167–94
[4] Jakob M et al 2020 The future of coal in a carbon-constrained climate Nat. Clim. Change 10 704–7
[5] Malik A et al 2020 Reducing stranded assets through early action in the Indian power sector Environ. Res. Lett. 15 094091
[6] Oei P-Y, Hermann H, Herpich P, Holtemöller O, Lünenburger B and Schult C 2020 Coal phase-out in Germany–implications and policies for affected regions Energy 196 117004
[7] Li M, Patiño-Echeverri D and Zhang J J 2019 Policies to promote energy efficiency and air emissions reductions in China’s electric power generation sector during the 11th and 12th five-year plan periods: achievements, remaining challenges, and opportunities Energy Policy 125 429–44
[8] Shan Y, Huang Q, Guan D and Hubacek K 2020 China CO₂ emission accounts 2016–2017 Sci. Data 7 1–9
[9] Normile D 2020 China’s bold climate pledge earns praise—but is it feasible? (https://science.sciencemag.org/content/370/6512/17)
[10] Zhang D, Wang J, Lin Y, Si Y, Huang C, Yang J, Huang B and Li W 2017 Present situation and future prospect of renewable energy in China Renew. Sustain. Energy Rev. 76 865–71
[11] Li M and Patiño-Echeverri D 2017 Estimating benefits and costs of policies proposed in the 13th FYP to improve energy efficiency and reduce air emissions of China’s electric power sector Energy Policy 111 222–34
[12] Tong D, Zhang Q, Zheng Y, Caldeira K, Shearer C, Hong C, Qin Y and Davis S J 2019 Committed emissions from existing energy infrastructure jeopardize 1.5 C climate target Nature 572 373–7
[13] Cui R Y et al 2019 Quantifying operational lifetimes for coal power plants under the Paris goals Nat. Commun. 10 1–9
[14] Tong D et al 2018 Current emissions and future mitigation pathways of coal-fired power plants in China from 2010 to 2030 Environ. Sci. Technol. 52 12905–14
[15] Tong D et al 2018 Targeted emission reductions from global super-polluting power plant units Nat. Sustain. 1 59–68
[16] Cui R Y et al 2021 A plant-by-plant strategy for high-ambition coal power phaseout in China Nat. Commun. 12 1–10
[17] Lu X, McElroy M B, Chen X and Kang C 2014 Opportunity for offshore wind to reduce future demand for coal-fired power plants in China with consequent savings in emissions of CO₂ Environ. Sci. Technol. 48 14764–71
[18] Dong Y, Jiang X, Liang Z and Yuan J 2018 Coal power flexibility, energy efficiency and pollutant emissions implications in China: a plant-level analysis based on case units Resour. Conserv. Recycl. 134 184–95
[19] Lu H, Wang C, Li Q, Wiser R and Porter K 2019 Reducing wind power curtailment in China: comparing the roles of coal power flexibility and improved dispatch Clim. Policy 19 623–35
[20] Lv T, Yang Q, Deng X, Xu J and Gao J 2020 Generation expansion planning considering the output and flexibility requirement of renewable energy: the case of Jiangsu Province Front. Energy Res. 8 39
[21] Sepulveda N A, Jenkins J D, De Sisternes F J and Lester R K 2018 The role of firm low-carbon electricity resources in deep decarbonization of power generation Joule 2 2303–20
[22] Collins S, Deane J P, Ponecet K, Panos E, Pietzcker R C, Delarue E and Gallachóir B 2017 Integrating short term variations of the power system into integrated energy system
models: a methodological review Renew. Sustain. Energy Rev. 76 839–56

[23] Geels F W, Berkhout F and van Vuuren D P 2016 Bridging analytical approaches for low-carbon transitions Nat. Clim. Change 6 576–83

[24] Lund P D, Lindgren J, Mikkola J and Salpakari J 2015 Review of energy system flexibility measures to enable high levels of variable renewable electricity Renew. Sustain. Energy Rev. 45 785–807

[25] Poncelet K, Delarue E, Duerinck J and D’haeseleer W China National Renewable Energy Center & NDRC 2020

[26] Doshi T 2021 The catastrophic texas blackouts: lessons for the developing countries Forbes (www.forbes.com/sites/tlakdoshi/2021/03/04/the-texas-catastrophic-blackout-lessons-for-the-developing-countries/?sh=46a39cb46481)

[27] Fouquet R 2016 Path dependence in energy systems and economic development Nat. Energy 1 1–5

[28] Alova G 2020 A global analysis of the progress and failure of electric utilities to adapt their portfolios of power-generation assets to the energy transition Nat. Energy 5 920–27

[29] Cui R et al 2020 A high ambition coal phaseout in China: feasible strategies through a comprehensive plant-by-plant assessment (College Park, MD: Center for Global Sustainability)

[30] Henderson C 2014 Increasing the flexibility of coal-fired power plants IEA Clean. Coal Cent. (London, UK) 15 (https://usea.org/sites/default/files/092014_Increasing%20the%20Flexibility%20of%20Coal-fired%20power%20plants_ccc242.pdf)

[31] Energiewende A 2017 Flexibility in thermal power plants—with a focus on existing coal-fired power plants (Berlin: Agora Energiewende) (www.agora-energiewende.de/fileadmin/Projekte/2017/Flexibility_in_thermal_plants/115_flexibility-report-WEB.pdf)

[32] Zhao Y, Liu M, Wang C, Li X, Chong D and Yan J 2018 Increasing operational flexibility of supercritical coal-fired power plants by regulating thermal system configuration during transient processes Appl. Energy 228 2375–86

[33] State Grid Corporation of China 2020 Introduction of State Grid in Jiangsu Province (available at: www.js.sgcc.com.cn/html/main/co/23/2014-11/25/2014112500035578884241_1.html) (Accessed 22 August 2020)

[34] Davidson M R, Zhang D, Xiong W, Zhang X and Karplus V J 2016 Modelling the potential for wind energy integration on China’s coal-heavy electricity grid Nat. Energy 1 1–7

[35] Sherman P, Chen X and McElroy M B 2017 Wind-generated electricity in China: decreasing potential, inter-annual variability and association with changing climate Sci. Rep. 7 1–10

[36] Sherman P, Chen X and McElroy M 2020 Offshore wind: an opportunity for cost-competitive decarbonization of China’s energy economy Sci. Adv. 6 eaax9571

[37] China National Renewable Energy Center & NDRC 2020 China Renewable Energy Outlook 2019 (Beijing: National Development and Reform Commission)

[38] Jia K 2016 It is imperative to increase the flexibility of the thermal power plants China Energy News

[39] Development and Reform Commission of Jiangsu 2019 Deepen the Reform of Price Formation of Electricity from Coal Power Plants in Jiangsu Province (Development and Reform Commission of Jiangsu)

[40] Jeong S-J, Kim K-S, Park J-W, Lim D and Lee S 2008 Economic comparison between coal-fired and liquefied natural gas combined cycle power plants considering carbon tax: Korean case Energy 33 1520–30

[41] Mongird K et al 2019 Energy Storage Technology and Cost Characterization Report (Richland, WA: Pacific Northwest National Lab. (PNNL))

[42] Cole W and Frazier A 2020 Cost Projections for Utility-Scale Battery Storage: 2020 Update (Golden, CO: National Renewable Energy Lab. (NREL))

[43] Parks G, Boyd R, Cornish J and Remick R 2014 Hydrogen Station Compression, Storage, and Dispensing Technical Status and Costs: Systems Integration (Golden, CO: National Renewable Energy Lab. (NREL))

[44] De Luna P, Hahn C, Higgins D, Jafer S A, Jaramillo T F and Sargent E H 2019 What would it take for renewable powered electrosynthesis to displace petrochemical processes? Science 364 eaav3506

[45] Goto K, Yogo K and Higashii T 2013 A review of efficiency penalty in a coal-fired power plant with post-combustion CO2 capture Appl. Energy 111 710–20

[46] Budinis S, Krevor S, Mac Dowell N, Brandon N and Hawkes A 2018 An assessment of CCS costs, barriers and potential Energy Strateg. Rev. 22 61