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The Changing Economics of China's Electricity System: Why Renewables and Electricity Storage may be a Lower Cost Way to Meet Demand Growth than Coal

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Abstract

Concerns around reliability in China's electricity sector have rekindled interest in a traditional solution: building more coal-fired generation. However, over the past decade China's electricity sector has seen significant changes in supply costs, demand patterns, and regulation and markets over the past decade, with falling costs for renewable and storage generation, "peakier" demand, and the creation of initial wholesale markets. These changes suggest that traditional approaches to evaluating the economics of different supply options may be outdated. This paper illustrates how a net capacity cost metric – fixed costs minus net market revenues – might be better suited to evaluating supply options in China. Using a simplified example with recent resource cost data, the paper illustrates how, with a net capacity cost metric, solar PV and electricity storage may be a more cost-effective option for meeting demand growth than coal-fired generation.

Recent resurgence in the Chinese economy and power shortages over the past two years appear to be prompting a new round of investment in coal-fired generation to reliably meet electricity demand. This analysis argues that electricity planners in China should consider changing their approach to evaluating the benefits and costs of different generation technologies. When they do, a combination of renewables and electricity storage will, or will soon, be more cost-effective than coal-fired generation. Building renewables and storage to meet electricity demand growth also allows for rapid expansion of supply, because these resources have relatively short construction times, and helps to reduce the risks of stranded coal power plant assets.

Background

China's electricity sector is in the midst of major structural changes, driven by technological innovation, economic change, and national policy. Costs for renewable generation and battery storage have fallen dramatically over the past decade. In many regions, solar and wind energy are now the cheapest source of electricity generation. National climate and air quality policies are also shifting China's electricity sector toward greater reliance on non-fossil fuel sources of electricity.

On the demand side, China's electricity demand is increasingly being driven by the service and residential sectors. Industrial demand for electricity fell from 73% of total demand in 2015 to 66% in 2022, with demand in the services and residential sectors growing around twice as fast as demand in industry.[1] Maximum electricity demand in industry tends to be relatively flat over time, whereas maximum demand in the services and residential sectors tends to be concentrated in a few weeks in summer and, in some regions, winter months. This shift from industry to services and residential as the main drivers of electricity demand will likely make China's electricity loads peakier.

These changes suggest that electricity resource planners and market participants in China should consider rethinking how they evaluate the economics of different electricity supply options, moving from a paradigm in which coal generation is the default supply resource for meeting demand growth, to one in which resource planners and market participants evaluate the economics of different resource options for meeting electricity demand growth on the basis of their net capacity costs.

This paper describes the rationale for using a net capacity cost metric in China and how it could be calculated and applied. It uses a simplified example with realistic cost data to show that, in some provinces, a combination of solar and battery storage may be more cost-effective for meeting growth in electricity demand than coal. It closes with a discussion of how the net capacity cost metric can be applied in resource planning and electricity markets.[2]

Changing Economics in China's Electricity System

Electricity systems that have high peak relative to average demand need to hold a significant amount of supply resources that are infrequently used. Figure 1 shows an example from California, where around 30% of generation capacity that is needed to reliably meet peak demand is used for less than 500 hours per year. Historically, natural gas combustion turbines have been built to meet peak demand in the U.S. because they are inexpensive to build, even though they have very high fuel costs. In other words, for

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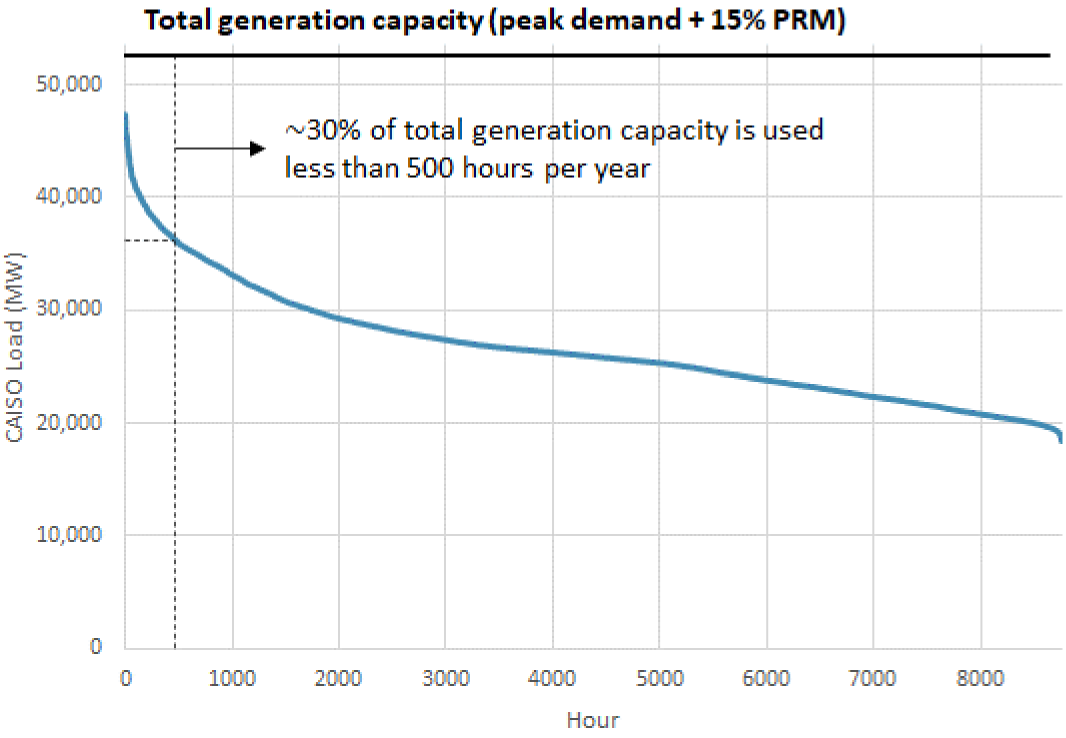
[1] Data are from CEC (multiple years).

[2] We do not conduct a province-specific analysis in this paper. Whether solar and storage is cost-effective for meeting demand growth will depend on a province's generation mix, solar resource endowment, and coal prices.

meeting infrequent periods of high demand what matters most is having low fixed costs rather than low variable generation costs.

Figure 1. Load Duration Curve for the California Independent System Operator (CAISO) Region, Illustrating the Large Amount of Infrequently Used Generation Capacity Needed to Reliably Meet Peak Demand



Notes: CAISO load duration curve is from 2015. California has historically used a 15% planning reserve margin (PRM) to account for load forest error and generator outages during peak periods. We did not have access to sufficient load data to develop accurate load duration curves for provinces in China.

To meet growth in peak demand at lowest cost, electricity planners in the U.S. find optimal resources by examining the net fixed (capacity) costs of different resources. In electricity markets, this net capacity cost metric is often referred to as the net cost of new entry (CONE). It is the total capital and fixed operations and maintenance (O&M) cost of the resource minus net margins for providing energy or ancillary services (benefits minus costs). It can be measured in terms of dollars per installed or dependable (firm) kW of capacity per year ($/kW-yr).

Example: Calculating and Using Net Capacity Costs

Resource planners are deciding between two new power plants (PP) to meet expected demand growth. PP1 is a baseload power plant that has installed costs of 4,000 yuan/kW, fixed O&M costs of 150 yuan/kW-yr, and an average net income (revenues minus costs) of 30 yuan/MWh during the 5,000 hours that it would operate. PP2 is a peaker plant that has installed costs of 3,000 yuan/kW, fixed costs of 50 yuan/kW-yr, and an average net income of 5 yuan/MWh during the 600 hours that it would operate. Both power plants would have a financial lifetime of 20 years and a weighted average cost of capital of 8%.

PP1 would have annualized capital costs* of 407 yuan/kW-yr (= 4,000 yuan/kW × 0.10185/yr) and total fixed costs of 557 yuan/kW-yr (= 407 yuan/kW-yr + 150 yuan/kW-yr). PP1's annual net revenues would be 150 yuan/kW-yr (= 30 yuan/MWh × 5,000 hours/yr × 1 MW/1,000 kW). Its net capacity cost would thus be 407 yuan/kW-yr (= 557 yuan/kW-yr – 150 yuan/kW-yr).

PP2 would have annualized capital costs of 306 yuan/kW-yr (= 3,000 yuan/kW × 0.10185/yr) and total fixed costs of 356 yuan/kW-yr (= 306 yuan/kW-yr + 50 yuan/kW-yr). PP2's annual net revenues would be 3 yuan/kW-yr (= 5 yuan/MWh × 600 hours/yr × MW/1,000 kW). Its net capacity cost would thus be 353 yuan/kW-yr (= 356 yuan/kW-yr – 3 yuan/kW-yr).

In this case, planners would choose PP2 (peaker) rather than PP1 (baseload). PP1 plant does not have large enough benefits (net income) to offset its higher annual fixed costs. Although PP2 has very low benefits, it also has much lower annual fixed costs. The relatively low benefits for PP1 suggest that this electricity system does not need more baseload generation.

This example illustrates how the net capacity cost metric can be used to evaluate and compare generating technologies that have different costs and provide different kinds of benefits to the electricity system. Having electricity markets is not necessary for using a net capacity cost metric. Either resource planning models or electricity market prices can be used to assess the benefits of different kinds of technologies.

* This example uses a simple capital recovery factor (CRF) to convert capital costs into annual principal and interest payments. The CRF is $r \times (1 + r)^t / [(1 + r)^t - 1] = 0.08 \times (1.08)^{20} / [(1.08)^{20} - 1] = 0.10185$.

In China, growth in electricity demand has often been met by building new coal-fired power plants. High energy (GWh) demand growth, declining capital costs for advanced coal generation technologies, and an "average dispatch" rule historically masked the economic and political costs of this strategy.[3] When new coal generation came online, average operating hours for coal units would fall but would increase again as demand caught up with supply. Due to declining capital costs for coal power plants, coal generation

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[3] Under this average dispatch (平均调度) rule, all thermal generators were operated roughly the same number of operating hours each year, regardless of fuel efficiency and operating cost (Kahrl et al., 2013). Since 2015, China's electricity reforms have aimed to facilitate a transition toward more competitive wholesale markets, in which lower marginal cost generators would operate more.

tariffs were often high relative to cost during periods of lower coal fuel costs, which meant that coal power plants could at least cover their costs over multi-year time horizons.

Going forward, however, this approach is likely to be challenged by slowing and peakier growth in electricity demand, the development of electricity markets and greater attention to economic efficiency, and declining costs for renewable generation and storage. Although net capacity cost has had limited traction in China as a metric for evaluating the economics of different supply options, in the future the combination of these drivers will likely make it more relevant.

Low-cost wind and solar generation and lower-cost electricity storage are already changing the economics of China's electricity system. When the levelized (yuan/MWh) costs of new wind and solar are lower than the operating (fuel plus variable O&M) cost of existing coal generation, building more wind and solar will lower total electricity costs by reducing fuel costs, even if this reduces operating hours for coal generators.[4] Wind and solar generation have near-zero operating costs, which means that, once built, maximizing their output under normal operating conditions will reduce total electricity supply costs.

In both China and the U.S., a key role for electricity storage has often been in providing operating reserves, and secondary control (frequency regulation) reserves in particular. For China, most electricity storage has historically been pumped hydropower but battery storage is becoming increasingly cost-effective as its costs decline. Batteries have the added benefit that they can be sited almost anywhere in the electricity system – from behind the generator meter, to the high voltage transmission system, to behind the customer meter –which means that they can provide locational services (e.g., grid congestion mitigation, reactive power support) as well as system-wide services like reserves and energy arbitrage.

When electricity storage is providing energy arbitrage and thermal generation is on the margin, the economics of storage will resemble a new efficient baseload power plant: its value will be the price spread between an off-peak period, when new efficient thermal units would be on or close to the margin, and an on-peak period, when less efficient, higher cost units are on the margin. When non-thermal generation is being curtailed, however, the economics of storage are very different: its value will be the price spread between near-zero marginal costs of non-thermal generation and the operating cost of higher cost thermal generation. Although these underlying economics of electricity storage still apply in China, changes in tariffs, markets, and operations may be needed to better reflect its system value.

Regardless of whether evaluation of the economics of new resources is done by electricity planners or through markets, the net capacity cost metric provides a useful way to compare the benefits and costs of different kinds of resources for meeting growth in demand. It can also provide intuition on interactions between renewable generation and coal and storage. The next section illustrates the application of net capacity costs for a situation in which coal, battery storage, and solar PV could be marginal resources.

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[4] Many provinces in China appear to already meet this criterion. As a less stringent criterion, when wind and solar generation costs all less than the all-in (total fixed plus variable) cost of new coal generation, building some amount of new wind and solar generation will reduce total electricity system costs by offsetting coal operating and fixed costs.

Applying Net Capacity Cost: An Illustrative Example Using Coal, Batteries, and Solar PV

This example compares different resource options – coal, battery storage, and solar PV – for meeting growth in peak (MW) and energy (GWh) demand. We include solar PV to illustrate interactions among resources, though in principle a comparison of resources to meet peak demand growth (capacity resources) would be more narrowly limited to coal generation and battery storage. The net capacity cost metric that the example uses is from a system perspective (cost per kW of incremental peak supply need), rather than from the perspective of individual resources (cost per kW of installed capacity).

Our example begins with 1,500 MW of growth in annual peak demand and 6,570 GWh of growth in annual energy demand.[5] This growth in peak and energy demand can be met using different combinations of resources. The example considers five strategies (cases) for meeting demand, described in Table 1.

Table 1. Five Cases Considered in this Example

Case 1	Coal meets all energy and peak demand growth
Case 2	Solar PV meets 70% and coal meets 30% of energy demand growth; solar meets peak demand growth based on its capacity credit and coal meets all residual peak demand growth
Case 3	Solar PV meets all energy demand growth; solar meets peak demand growth based on its capacity credit and coal meets all residual peak demand growth but provides no energy
Case 4	Solar PV meets all energy demand growth; solar meets peak demand growth based on its capacity credit and battery storage meets all residual peak demand growth; battery storage provides frequency regulation reserves
Case 5	Solar PV meets all energy demand growth; solar meets peak demand growth based on its capacity credit and battery storage meets all residual peak demand growth; battery storage provides energy arbitrage

In the different cases, resources are sized based on how much they can reliably contribute to peak supply needs (capacity credits) and annual energy needs (annual capacity factors). Table 2 shows installed capacities of different resources by case, using assumptions for capacity credits and annual capacity factors described in the table notes. All of the calculations in this example can be done on a per unit basis, meaning that the total peak and energy demand growth assumptions are largely irrelevant for the results,[6] though using these totals helps to provide intuition.

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[5] For simplicity, we assume that any planning reserve margin is already included in peak demand growth. The implied system load factor of 0.5 (= 6,570 h/8,760 h * 1,000 MW/GW / 1,500 MW) is low enough to accommodate some amount of planning reserve margin.

[6] The main structural issue with demand growth is peak demand growth relative to energy demand growth, which will have a significant impact on the value of new baseload generation. The scale of demand growth is only relevant for its cost implications on resources (e.g., in the short-term solar PV may become more expensive with more deployment as the highest quality resources are deployed) and constraints on the total annual deployment of different kinds of resources.

Table 2. Installed Capacities by Resource by Case

Resource	Case 1	Case 2	Case 3	Case 4	Case 5
Coal	1,667 MW	1,083 MW	833 MW		
Battery				833 MW	833 MW
Solar PV		2,625 MW	3,750 MW	3,750 MW	3,750 MW

Notes: We assume capacity credits of 0.9 for coal, 0.9 for batteries, and 0.2 for solar PV. The coal and battery capacity credits account for forced outages and, for batteries, energy limits. We assume an annual capacity factor of 0.2 for solar PV. In case 2, solar PV capacity is sized to 70% of growth in annual energy demand (4,599 GWh = 6,570 GWh × 70%) and contributes 20% of its nameplate capacity to peak demand needs (525 MW = 4,599 GWh / [0.2 × 8,760 hrs/yr] × 1,000 MW/GW × 0.2); coal generation capacity is sized to residual capacity need (1,083 MW = [1,500 MW – 525 MW] / 0.9). In case 3, solar PV is sized to 100% of annual energy demand (6,570 GWh), giving a coal installed capacity of 833 MW (= [1,500 MW – 6,570 GWh / (0.2 × 8,760 hrs/yr) × 1,000 MW/GWh × 0.2] / 0.9).

All cases use the fixed costs in Table 3. Overnight capital costs are construction costs, per unit of installed capacity. Annualized capital costs include financing costs, converting overnight capital costs (yuan/kW) into an annual (yuan/kW-yr) value. Total capacity costs are annualized capital costs plus fixed operations and maintenance (O&M) costs.

Table 3. Fixed Costs and Fixed Cost Assumptions by Resource

Resource	Overnight capital costs (yuan/kW)	Economic lifetime	Annualized capital costs (yuan/kW-yr)	Fixed O&M costs	Total annual capacity cost (yuan/kW-yr)
Coal	3750	20	382	130	512
Battery	6000	15	701	150	851
Solar PV	3500	20	356	45	401

Sources and notes: Overnight capital costs for coal, batteries, and solar PV are from are China estimates from Bloomberg New Energy Finance data. Fixed O&M costs for coal and solar PV are from BNEF. Fixed O&M costs for batteries are based on 2.5% of capital costs, from the U.S. National Energy Renewable Laboratory's (NREL's) Annual Technology Baseline (ATB). Economic lifetimes for coal and solar PV are based on rules-of-thumb; economic lifetime for batteries is based on ATB. We assume that all resources have a weighted average cost of capital of 8%. See the box on Calculating and Using Net Capacity Costs for how total capacity costs are calculated.

We assume that system marginal costs vary during off-peak and on-peak periods. During off-peak periods, efficient units (300 kgce/MWh net heat rates) are on the margin; during on-peak periods, less efficient units (350 kgce/MWh) are on the margin. We assume an average coal price of 800 yuan/tce.[7] During 5% of hours, wind, solar, and hydropower are on the margin and are being curtailed, leading to a marginal costs of zero during these periods.[8] Based on U.S. electricity market prices, we assume that marginal costs for frequency regulation reserves are, on average, 30% of energy marginal costs.[9] Table 4

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[7] Thermal coal prices in China have seen significant volatility in recent years. This fuel cost is intended to be a middle of the road estimate. As a higher end point of comparison, the CEC's CECI index was roughly 1,200 yuan/tce in April 2023. See https://www.cec.org.cn/menu/index.html?718.

[8] Five percent is a generic assumption. The analysis assumes that these energy price and curtailment trends continue, in real terms, over the economic lifetime of new resources.

[9] In 2018, average frequency regulation prices as a share of energy prices in different U.S. ISOs were: CAISO: 42%/42% (reg up/down); ERCOT: 49%/16%; ISO-NE: 89%; MISO: 41%; NYISO: 43%; PJM: 58%; SPP: 39%/26%. CAISO, ERCOT, and SPP have separate upward and download regulation products, whereas the other ISOs have a single bidirectional regulation product.

shows the system marginal costs for energy and frequency regulation reserves that result from these assumptions.

Table 4. System Marginal Costs

System marginal cost			
Off-peak	**On-peak**	**Curtailment hours**	**Frequency regulation reserves**
270 yuan/MWh	310 yuan/MWh	0 yuan/MWh (5% of hours)	86 yuan/MW-h

Notes: On-peak and off-peak system marginal costs are calculated as net heat rate multiplied by coal price plus a variable O&M adder of 30 yuan/MWh. We define on-peak as hour beginning 10:00 to hour ending 20:00. Frequency regulation reserve marginal costs are a weighted average of 30% of off-peak and on-peak marginal costs.

Different resources provide different value to the electricity system depending on how and when they operate. Table 5 shows average unit value and annual value for new coal, battery storage, and solar PV resources in different cases based on the system marginal costs in Table 4. These values assume that the marginal costs in Table 4 remain constant over time.[10] The average unit value for new coal units is the difference between off-peak and on-peak system marginal costs, which assumes that new coal would be on the margin during off-peak. When batteries are providing frequency regulation, their unit value is the average marginal cost of frequency regulation; when they are providing energy arbitrage, their unit value is the spread between off-peak and on-peak marginal costs (accounting for 5% curtailment), net of battery losses, plus a small adder (1.1x) for the real-time value of battery flexibility.[11] The average unit value of solar PV is off-peak and on-peak system marginal costs, weighted by the share of solar PV generation during off-peak and on-peak periods. Annual value is average unit value multiplied by a capacity factor. The notes to Table 5 provide a more detailed description of assumptions used in the value calculations.

Table 5. Unit and Annual Value for Coal, Battery Storage, and Solar PV in Different Cases

	Case 1	Case 2	Case 3	Case 4	Case 5
Average unit value					
Coal	17 yuan/MWh	17 yuan/MWh	17 yuan/MWh		
Battery				86 yuan/MW-h	47 yuan/MWh
Solar PV		302 yuan/MWh	302 yuan/MWh	302 yuan/MWh	302 yuan/MWh
Annual value					
Coal	88 yuan/kW-yr	88 yuan/kW-yr	0 yuan/kW-yr		
Battery				603 yuan/kW-yr	70 yuan/kW-yr
Solar PV		529 yuan/kW-yr	529 yuan/kW-yr	529 yuan/kW-yr	529 yuan/kW-yr

Notes: For coal, unit value is the spread between on-peak and off-peak marginal costs (40 yuan/MWh) weighted by the share of on-peak hours (42%). Annual value is unit value multiplied by assumed capacity factors of 0.60 (5,256 hrs/yr, case 1), 0.60 (case 2), and 0 (case 3). Coal capacity factor is 0 in case 3 because we assume that the coal unit is not needed to provide energy and that, under normal conditions, it does not operate. We assume that all

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[10] Unit and annual values should be the annualized net present value (NPV) of these resources over some time horizon, for instance 10 to 20 years. However, given the difficulty of projecting system costs over time, we assume that costs remain constant.

[11] Batteries can start and ramp instantaneously, which means that they can resolve real-time system issues that slower starting and ramping coal units cannot. This real-time value is system specific and difficult to assess. The multiplier value that we use here (1.1x) is conservatively low.

curtailment occurs during off-peak hours, which means that curtailment does not affect coal unit value. For battery storage, unit value is the average frequency regulation reserve price (case 4) and the spread between off-peak and on-peak prices (40 yuan/MWh for 95% of hours, 310 yuan/MWh for 5% of hours) multiplied by a roundtrip efficiency of 81% plus a real-time energy multiplier equivalent to 1.1 multiplied by energy price spreads net of losses. We assume that batteries provide reserve energy equivalently in both directions, leading to negligible average costs for providing regulation reserves over time. Annual value assumes that batteries provide average reserves equivalent to 80% of their nameplate capacity[12] (case 4) and one charge and discharge cycle per day (case 5). For solar PV, unit value assumes that 80% of solar generation is on peak, based on a generic solar PV profile, and a generic capacity factor of 0.2.

Each resource's net capacity cost will be the total annual capacity costs in Table 3 minus the annual value in Table 5. These net capacity costs are per kW of installed capacity, rather than per kW of incremental system need. The system net capacity cost converts from the former to the latter by multiplying by the ratio of installed capacity for each resource in each case (Table 2) to peak demand growth (1,500 MW). Total system net capacity costs are the sum of system net capacity costs for each resource. Table 6 shows resource and system net capacity costs for each resource, and total system net capacity costs by case. The total system net capacity cost is the net cost of meeting peak demand growth with the combination of resources in the case. The resource net capacity cost is the annual revenue shortfall (positive sign) or surplus (negative sign) from providing energy and ancillary services.

Table 6. Resource and System Net Capacity Cost by Resource and Case

	Case 1	Case 2	Case 3	Case 4	Case 5
Resource net capacity cost (yuan/kW-yr, per kW of installed capacity)					
Coal	424	424	512		
Battery				248	781
Solar PV	401	-128	-128	-128	-128
System net capacity cost (yuan/kW-yr, per kW of firm capacity used to meet peak demand)					
Coal	471	306	236		
Battery				138	434
Solar PV		-223	-319	-319	-319
Total	471	83	-83	-181	115

Notes: The weighting that we use to calculate system net capacity costs is based on the ratio of installed capacity and peak demand growth. For instance, in case 2, the system net capacity cost of coal is 259 yuan/kW-yr = 424 yuan/kW-yr × 1,083 MW / 1,500 MW. This is the system cost of meeting an incremental kW of peak demand growth with coal and solar PV, assuming that 70% of new energy demand is met with solar PV and 30% with coal and that coal provides 0.72 kW (= 1,083 MW / 1,500 MW) to meet each incremental kW of peak supply.

The results in Table 6 indicate that solar PV is a negative cost (a cost savings), both from an individual resource and a system perspective. This means that any new solar PV generation will be profitable for resource owners and will reduce system costs, which implies that resource planners should try to maximize the amount of solar generation. Among cases, the lowest cost option is case 4 (solar + batteries, frequency regulation), which has a total system net capacity cost of -181 yuan/kW-yr, meaning that it reduces costs by 181 yuan/kW-yr. There are limits to the amount of battery storage that would be cost-effective, as frequency regulation reserve markets tend to be relatively small. In the U.S., for instance, system operators typically procure average regulation reserves equivalent to 1% of peak

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[12] This assumption is based on Kahrl et al. (2021).

demand.[13] In China, this might imply average regulation reserve quantities in each province on the order of 500 to 1,500 MW, or on the order of 30-40 GW nationally.[14]

The second lowest cost option is case 3 (solar + coal backup, -83 yuan/kW-yr), though it is unclear if it would be political acceptable in China to build large new coal plants and only operate them for a few hundred hours per year. If new coal plants are built solely to back up solar and are allowed to run at higher capacity factors, this would lead to economically inefficient outcomes because new coal plants are only needed for capacity (peak period energy) rather than energy. The result would be inefficiently depressed net income for existing generators, a situation that is also not likely to be politically acceptable.

Case 2 (solar 70%, coal 30%, 83 yuan/kW-yr) is slightly lower cost than case 5 (solar + batteries, energy arbitrage, 115 yuan/kW-yr), but this comparison is sensitive to changes in several assumptions: installed costs for battery storage, the frequency of curtailment hours, the real-time value of storage, and the policy-driven lifetime of coal units. Of these, the most important and uncertain assumption is likely battery storage costs. If installed costs decline by around 7% (to ~5,600 yuan/kW), case 2 and case 5 have equivalent total system net capacity costs (83 yuan/kW-yr). Case 1 (coal) is the least economic option for meeting demand growth.

The results in Table 6 mimic the outcomes of resource planning models or bidding economics in wholesale electricity markets. The system net capacity cost metric mirrors the calculations in a least-cost capacity expansion model, which essentially minimizes fixed costs net of system value. It also captures decision-making in a wholesale market. The resource net capacity costs would be equivalent to bids in a capacity market.[15]

Conclusions and Discussion

Structural changes in China's electricity system are changing its economics, as the system continues to shift from a coal-dominant system with large industrial demand to one with in which non-fossil fuel resources account for most generation and demand is increasingly driven by the service and residential sectors. As the underlying economics change, new metrics are needed to evaluate and compare different supply options. In the U.S., resources are typically compared on the basis of net capacity cost. We believe that this metric could be useful in China as well.

Using a net capacity cost metric, we compared three different supply options for meeting growth in peak and energy demand: coal generation, battery storage, and solar PV. The results suggest that, under the cost assumptions used in the analysis, the current cost of solar PV generation is lower than the operating cost of coal units, which implies that all new solar generation will lower system costs and that any new capacity resources built to meet demand growth should be sized to account for growth in solar PV. Among the resource combinations we compared, solar PV plus battery storage will likely be the lowest net cost option for meeting demand growth in areas where battery storage can provide frequency regulation reserves. Once regulation reserve markets are saturated, battery storage would likely need reductions in installed costs on the order of 10% (to ~5,600 yuan/kW), for instance through increased

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[13] Kahrl et al. (2021).

[14] This assumes provincial peak demands of 50-150 GW.

[15] If the capacity market is for unforced capacity, the resource net capacity costs would be adjusted by capacity credits that reflect forced outage rates and energy-limits.

manufacturing scale or lower installation costs due to hybridization with solar generation, to be cost-effective as an alternative to using coal generation as a backup for solar PV. Given the dynamism in markets for batteries, these cost reductions may have already occurred. Higher coal prices would also improve the economics of battery storage.

Although the example in this brief focused narrowly on coal, battery storage, and solar PV, the results are more broadly applicable to any renewable resource. The main differences will be in installed cost and resource profiles and system values. As long as the annual value (Table 5) of renewable generation exceeds the total annual capacity cost (Table 3), the lowest cost resource planning strategy will be building capacity resources that accommodate growth in renewable generation.

The results suggests that a near-term strategy in China might be to enable battery storage participation in the provision of operating reserves, which would encourage continued innovation in and cost reductions for battery storage systems and would allow system operators to gain more operational experience with batteries. This strategy would be consistent with market outcomes and is consistent with recent electricity market experience in the U.S. and Europe.[16] It would help to resolve near-term capacity and energy needs, as batteries and solar PV generation can typically be developed more quickly than coal generation. It would also help to alleviate future conflicts between new coal generation and renewable energy, as building new coal generation that is only needed as a backup for renewable generation will either rarely operate, will depress operating hours and net income for other existing coal generators, or will create new stranded asset risks.

Continued electricity market reforms could help to enable more efficient investments in renewable generation and electricity storage, as well as their integration into electricity systems. Pricing wholesale electricity based on system marginal costs and allowing renewable generation and electricity storage to participate in wholesale markets would increase the value of these resources and enhance their business case. Allowing renewable generation and electricity storage to participate in wholesale markets would also encourage efficient utilization of these resources. Solar and wind have near-zero marginal costs and thus integrating them into system dispatch can help to maximize their uptake and reduce fuel costs. Electricity storage can provide a variety of functions for the electricity system; wholesale prices can help to guide the operation of storage toward those functions that have the highest value at the lowest cost.

Additional supply alone will not be the lowest cost way to meet growth in electricity demand in China. Continued efforts to improve end-use efficiency and demand response will help to reduce the overall cost of supplying electricity. As China moves toward wholesale electricity markets, regional market designs and regional approaches to resource adequacy that encourage resource sharing among provinces will also help to reduce costs, by reducing the total amount of generation capacity needed to reliably meet demand.

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[16] In the U.S., utility-scale batteries are mostly providing frequency regulation in ISO markets (EIA, 2021). In Europe, initially batteries mostly provided primary frequency reserves but, as these markets began to saturate, moved into other reserve markets (Forsyth, 2020).

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