How do price caps in China's electricity sector impact the economics of coal, power and wind? Potential gains from reforms

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Electronic appendix 1. Mathematical formulation of China's electricity sector

Table A.1: Indices, variables and constants

Indices	$\boldsymbol{i}; \boldsymbol{i^n}; \boldsymbol{i^w}$	Capacity type; Spinning reserve; Wind
	r, r'	Region
	$l; l'; p$	Load segment; Peak load segment
	j	Wind capacity increment
	$f; f^a; f^o$	Fuels; Coal; Other fuels (oil, gas, uranium)
	k	Fuel supply step (only f^o)
	c, s	Calorific value; Sulfur content (*coal only*)
Variables	$\boldsymbol{x}_{i,l,r}$	Amount of capacity generating in load segment l in MW
	$\boldsymbol{y}_{i^n,l,r}$	Amount of capacity used for spinning reserves in MW
	$\boldsymbol{z}_{i,r}$	New capacity built
	$\boldsymbol{t}_{l,r,r'}$	Electricity transmission in MWh
	$\boldsymbol{u}_{r,r'}$	New transmission capacity
	$\boldsymbol{\theta}_{i^w,n,r}$	Level of wind operation
	$\boldsymbol{v}_{i,f,c,s,k,r}$, $\boldsymbol{v}_{i,f^o,k,r}$	Fuel consumption coal and other fuels
	$\boldsymbol{q}_{i^w,r}$	Subsidy for wind generators
	$\boldsymbol{\pi}_{f,c,s,r}$	Fuel price
Constants	$S_{i,r}$	Allowed generators' financial losses (including subsidies)
	$\tilde{v}_{f^c,c,s,r}$	Non-power coal consumption
	$E_{i,r}; Et_{r,r'}$	Existing capacities: generation; transmission
	$D_{l,r}; H_l$	Power demand in MWh; hours in load segment
	G_i	Internal electricity use coefficient
	$Y_{r,r'}$	Transmission yield
	$T_{l,l',r,r'}$	Mapping coefficient between load segments of different regions
	$\hat{P}_{i,r}$	On-grid tariff caps
	$OM_i; Ot_{r,r'}$	O&M costs: generation; transmission
	$K_i; Kt_{r,r'}$	Annualized capital and fixed costs: generation; transmission
	C_c	Conversion to Standard Coal Equivalent

Constants	$F_{i,f,r}$	Power plant heat rate
	$B_{f,k,r}$	Bound on step k for fuel
	a	Spinning reserves requirement as fraction of wind capacity
	b	Fraction of fuel and variable costs consumed by spinning reserves
	I_j	Size of wind capacity increments in MW
	$\Delta_{j,l,r}$	Reduction in load in segment l for each wind increment
	W	Capacity target in the wind policy
	DW_l	Dry weight of sulfur
	$EC_i^{SO_2}; EC_i^{NO_x}$	Coefficients for emissions control: SO_2; NOx
	$N_{i,c,r}$	NOx emissions per unit of coal consumed
	$T_r^{SO_2}; T_r^{NOx}$	Total emissions limit: SO_2, NOx

Although the model is formulated as an MCP, rather than present the primal, dual, and complementarity conditions, it is simpler to present a linear program that models the case without price caps, and then show the features that require an MCP in the presence of price caps. Since the focus of the paper is on the electricity market, here we detail just the representation of China's electricity sector, which means for the model to be complete, the objective function contains a cost term for the coal that is delivered to utilities. In a combined coal and utilities model this term would be removed and replaced by coal material balances in the constraints that feed coal to utilities. A description of the coal supply model is presented in Rioux et al. (2016).

In the electricity sector every regional utility acts as a monopsonist that minimizes the total cost of supplying and transmitting power. The model minimizes the total cost over all of the regions simultaneously. This means each utility minimizes its costs and trades electricity with the other utilities at prices set to marginal costs.

We first present the model under the Long-run without caps scenario because it can be formulated as a linear program both standalone and combined with the coal model. We then add the constraint that captures the consequences of the price caps, explaining why this change requires an MCP formulation in the integrated model.

The mathematical program for the scenario without price caps is:

$$min \sum_{i,l,r} OM_i \cdot \left(\boldsymbol{x}_{i,l,r} + b \cdot \boldsymbol{y}_{i^n,l,r}\right) \cdot H_l + \sum\nolimits_{i^n,r} K_{i^n} \cdot \boldsymbol{z}_{i^n,r} + \sum\nolimits_{i,f,c,s,k,r} \boldsymbol{\pi}_{f,c,s,r} \cdot \boldsymbol{v}_{i,f,c,s,k,r}$$

$$+ \sum\nolimits_{r,r'} Kt_{r,r'} \boldsymbol{u}_{r,r'} + \sum\nolimits_{l,r,r'} Ot_{r,r'} \boldsymbol{t}_{l,r,r'} - \sum\nolimits_{\boldsymbol{i^w},r} \boldsymbol{q}_{i^w,r}$$

Subject to the following constraints:

Fuel material balances:

$$\sum\nolimits_{(c,s,k)} \boldsymbol{v}_{i,f,c,s,k,r} \cdot C_c - \sum\nolimits_l F_{i,f,r} \cdot H_l \cdot \left(\boldsymbol{x}_{i,l,r} + b \cdot \boldsymbol{y}_{i^n,l,r}\right) \geq 0 \qquad \text{(A.1)}$$

Supply constraints for fuel other than coal:

$$\sum\nolimits_i \boldsymbol{v}_{i,f^o,k,r} \leq B_{f^o,k,r} \qquad \text{(A.2)}$$

Capacity limits for power generation and transmission:

$$\boldsymbol{z}_{i,r} - \boldsymbol{y}_{i^n,l,r} - \boldsymbol{x}_{i,l,r} \geq -E_{i,r} \qquad i \neq i^w \qquad \text{(A.3)}$$

$$\boldsymbol{u}_{r,r\prime} - \sum\nolimits_l \boldsymbol{t}_{l,r,r\prime} \geq -Et_{r,r\prime} \qquad \text{(A.4)}$$

Power transmitted constrained by the amount produced:

$$\sum\nolimits_i H_l \cdot G_i \cdot \boldsymbol{x}_{i,l,r} - \sum\nolimits_{r\prime} \boldsymbol{t}_{l,r,r\prime} \geq 0 \qquad \text{(A.5)}$$

Power demand:

$$\sum\nolimits_{r\prime,l\prime} Y_{r\prime,r} \cdot T_{l\prime,l,r\prime,r}, \cdot \boldsymbol{t}_{l\prime,r\prime,r} \geq D_{l,r} \qquad \text{(A.6)}$$

Reserve margin:

$$\sum\nolimits_{i \neq i^w} \left(\boldsymbol{z}_{i,r} + E_{i,r}\right) \geq 1.1 \cdot D_{p,r} \qquad \text{(A.7)}$$

Wind operation:

$$\boldsymbol{z}_{i^w,r} - \sum\nolimits_n I_n \cdot \boldsymbol{\theta}_{i^w,j,r} \geq -E_{i^w,r} \qquad \text{(A.8)}$$

$$\sum\nolimits_{i^w} \boldsymbol{\theta}_{i^w,j,r} \leq 1 \qquad \text{(A.9)}$$

$$\sum\nolimits_{\boldsymbol{n}} \Delta_{j,l,r} \cdot I_j \cdot \boldsymbol{\theta}_{i^w,j,r} - \boldsymbol{x}_{i^w,l,r} \geq 0 \qquad \text{(A.10)}$$

Added spinning reserve requirement for wind power:

$$\sum_{i^n} \boldsymbol{y}_{i^n,s,r} - \sum_{i^w,j} a \cdot \Delta_{j,l,r} \cdot \boldsymbol{\theta}_{i^w,j,r} \geq 0 \tag{A.11}$$

Meeting the wind capacity target:

$$\sum_r z_{i^w r} \geq W - \sum_r E_{i^w r} \tag{A.12}$$

Regional sulfur emissions:

$$\sum_{(c,s)} \left(\sum_{i,f^a} \boldsymbol{v}_{i,f^a,c,s,k,r} \cdot EC_i^{SO_2} + \tilde{v}_{c,s,r} \right) \cdot DW_s \cdot 1.6 \leq T_r^{SO_2} \tag{A.13}$$

Nitrous oxide emissions:

$$\sum_{i,f^a,c} \left(\boldsymbol{v}_{i,f^a,c,s,k,r} \cdot N_{i,c,r} \cdot EC_i^{NOx} \right) \leq T_r^{NOx} \tag{A.14}$$

$$y_{i^n(i),l,r} > 0,\ x_{i,l,r} \geq 0,\ q_{i^w(i),r} \geq 0,\ u_{r,r'} \geq 0,\ t_{l,r,r'} \geq 0 \tag{A.15}$$

Note that the transmission variables between regions r' and r, $T_{l',l,r',r}$, link different load segments, with the electricity produced in one load segment in one region distributed over multiple load segments in another region. This allows the model to match the same times in the load duration curves of the different regions and capture the effects of non-coincident peaks in the value of generation and transmission.

In the standalone electricity model the $\boldsymbol{\pi}_{f,c,s,r}$ for coal are constants, making the model a linear program. In the integrated model without price caps we combine the objective functions of the two models and we remove the term $\boldsymbol{\pi}_{f,c,s,r} \cdot \boldsymbol{v}_{i,f,c,s,k,r}$ for coal from the objective function. We add material balance constraints that link the coal model to the utilities model and the price of coal comes from the dual variables of these constraints.

We now add the profitability constraint that measures the effects of the price caps. Adding this constraint to the integrated coal and utilities model means there is no corresponding optimization problem to the MCP.

For coal we redefine $\boldsymbol{\pi}_{f,c,s,r}$ to be the set of dual variables associated with the material balances constraints that link the coal transportation network to the utility model. The profitability constraint requires that the generators in a region be profitable over all of their equipment and allows them to lose money on some plants as long as they make it up on other plants.

$$\sum_i \left[\left(\hat{P}_{i,r} \cdot G_{i,r} - OM_i \right) \left(\sum_l H_l \cdot \boldsymbol{x}_{i,l,r} \right) - \sum_{f,c,s} \boldsymbol{\pi}_{f,c,s,r} \cdot \boldsymbol{v}_{i,f,c,s,r} + S_{i,r} \right]$$
$$- \sum_{i^n,l} OM_{i^n} \cdot b \cdot W_s \cdot \boldsymbol{y}_{i^n l,r} - \sum_i K_i \cdot \left(\boldsymbol{z}_{i,r} + E_{i,r} \right) \geq 0 \qquad \text{(A.16)}$$

The first term is what the revenues would be at the price caps less the operating and maintenance costs, the second is the fuel costs, the fourth is the operating and maintenance costs for the spinning reserve and the fifth is the annualized cost of capacity. The second term, $\boldsymbol{\pi}_{f,c,s,r} \cdot \boldsymbol{v}_{i,f,c,s,r}$, is the product of a primal and dual variable, which can appear in an MCP but not in an optimization model.

The third term in (A.16) is a subsidy that is added as a constant to make this constraint feasible, as generators received government subsidies and reported financial losses in 2012. We found that this constraint cannot be met without a subsidy, given the shape of the load duration curve and the requirement to have spinning reserves to back up the wind generators. We iterate to find the smallest subsidy necessary for the model to be feasible. That is, we have a mathematical program subject to equilibrium constraints where the government is minimizing the subsidy needed to make generators profitable subject to the market equilibrium.

Electronic appendix 2. Model calibration

The model, calibrated to 2012 data[1], contains 12 regions, aggregating adjacent provinces with similar cost structures, on-grid tariff caps and shared grid resources. A total of 21 coal supply nodes are used to capture the geographic dispersion of resources. Every regional load curve is split into five load segments. Since demand is represented by a load duration curve, only one non-dispatchable renewable generator can be included. We selected wind, by far the largest source of non-dispatchable power in 2012.

Regional power producers have 10 different generator types (14 when considering emission controls). Transmission capacities are split into High Voltage Alternating Current (AC) and Direct Current (DC) interregional transmission lines. Data sources are listed in table A.2.

Table A.2: Power sector model calibration data

Data	Sources
Power demand (data used to construct load curves)	Li et al. (2007), Atong et al. (2012), Wei et al. (2010), Wang et al. (2013), Yang (2009), Ma et al. (2011), Cheng et al. (2013), Bai and Li (2010), Hou (2007), Cheng (2007), Liu et al. (2009), Yu et al. (2011), IHS (2014).
Existing generation capacities	Platts (2015),IHS (2015)
Fuel demand	NBS (2013), CEIC (2016)
Fuel prices	NDRC
Capital discount rate	Dong (2012)
Power plant capital costs and gross thermal efficiencies	IEA WEIO (2014)
Power plant fixed and variable costs	IEA WEIO (2014), WEC (2010)
SO_2 and NOx emission factors	Schreifels et al. (2012)
Regional SO_2 and NOx emissions	MEP (2013)
Capital and variable cost of SO_2 (FGD) and NOx (SCR) controls	Zhang (2006)
NOx flue gas concentration range	Zevenhoven and Kilpinen (2001)
On-grid tariff caps, tariff levels, SO_2 and NOx tariff supplements	NDRC, China Resource Power Holdings (2012)

[1] We also recalibrated Rioux et al.'s (2016) model on 2012 data.

Existing and planned power transmission capacities	NEA (2015), NDRC (2015), SASAC, China Resource Power Holdings (2012), Jineng Group (2014), People's Daily (2014)
Transmission costs	Cheng (2015)
Interregional and intraregional transmission losses UHV-DC and HV-AC	IEA ETSAP (2014), The World Bank (2016), China Southern Power Grid (2013), Cheng (2015)
Capital cost, UHV-DC and HV-AC	State Grid Corporation of China (2013), SASAC (2007), Zhang (2014), Yang and Gao (2015), Paulson Institute (2015)
On-grid tariffs	NDRC (2011)
Regional wind resources and profiles	He et al. (2014), Yu et al. (2011)

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