Appendix A: Sources and Organization of Electricity Price and Production Data

We distinguish four categories of electricity. For electricity produced in a given province, we distinguish:

- electricity sold in the province at administered prices
- electricity sold in the local (provincial) market
- electricity sold in the zonal market
- electricity sold outside the province at administered prices

This appendix describes how we organize the price and output data for electricity in each of these categories.

1. Electricity Prices

For each province, we define the electricity prices p_1, p_2, p_3, and p_4 as the prices associated with the above four categories of electricity sold, respectively.

The administered prices p_1 for electricity sold in each of 29 provinces were obtained from China's National Development and Reform Commission. These prices are inclusive of subsidies for desulfurization, denitrification, and soot removal.

Data on local and zonal market prices of electricity (p_2 and p_3) were collected from China's Electric Power Development Research Institute. For some provinces, these data were not available, so we needed to introduce some assumptions to fill the data set with these prices for all 29 provinces.[1]

For each province for which data on administered local prices were available, we first calculated $p_{2\_weighted}$, the production-weighted average local market price of all the local tradings by all units in the province. Similarly, we calculated $p_{3\_weighted}$, the production-weighted average zonal price of all zonal tradings by units within the province. We then assigned $p_{2\_weighted}$ and $p_{3\_weighted}$ as p_2 and p_3 for these provinces.

[1] Data on p_2 were unavailable for the following provinces: Beijing, Tianjin, Shanghai, Gansu, Qinghai, Ningxia, Xinjinag, Sichuan, and Yunnan. Data on p_3 were unavailable for the following provinces: Beijing, Tianjin, Shanxi, Shandong, Shanghai, Fujian, Hubei, Hunan, Jiangxi, Jilin, Heilongjiang, Inner Mongolia, Qinghai, Ningxia, Xinjiang, Sichuan, and Guizhou.

If data on a province's local market prices were not available , we assigned p_2 as the sum of the province's p_1 and the average of differences between $p_{2\_weighted}$ and p_1 across the provinces for which $p_{2\_weighted}$ could be calculated.

If data on a province's zonal market prices were not available, we obtained the province's p_3 by adding the average of differences between $p_{3\_weighted}$ and p_2 across the provinces for which $p_{3\_weighted}$ could be calculated.

Data on p_4, the administered prices of electricity sold outside provinces, were not available. To construct these data, we assume that, for each province, the difference between the out-of-province administered price p_4 and the zonal market price p_3 is the same as the average difference between between the province-level prices p_2 and p_1.

2. Electricity Production

Data on electricity production were collected from China Electricity Council and National Energy Administration. Table A1 summarizes the two sets of data collected: (1) total electricity production by province in 2016 and the national electricity production by category in 2016; and (2) ratios between electricity sold at administered prices and market prices on provincial and national levels in 2018.

Table A1: Available Data on Electricity Production

	Provincial	National
2016	$X_{TOT,P}^{2016}$	$X_{1,N}^{2016}$, $X_{2,N}^{2016}$, $X_{3,N}^{2016}$, $X_{4,N}^{2016}$, $X_{TOT,N}^{2016}$
2018	m_P^{2018}	m_N^{2018}

Notation:

The subscripts P and N indicate provincial and national levels, respectively.

X_1: quantity of electricity sold at the administered price within the province;
X_2: quantity of electricity sold in the provincial (local) market;
X_3: quantity of electricity sold in the zonal market;
X_4: quantity of electricity sold outside the province at the outside-of-province administered price;
X_{TOT} : total electricity sold;

m: ratio between administered electricity and marketed electricity, i.e., m=(X_1 + X_4) / (X_2 + X_3) .

For each of the 29 provinces, we obtained electricity production by technology category as follows. Using the national data for 2016, we computed

$$m_N^{2016} = (X_{1,N}^{2016} + X_{4,N}^{2016}) / \left(X_{2,N}^{2016} + X_{3,N}^{2016}\right)$$

This is the ratio of all administered electricity to all marketed electricity at the national level. From this we calculated the change in m from 2016 to 2018:

$$\%m = m_N^{2018} / m_N^{2016}$$

To obtain 2016 numbers at the provincial level, we assumed that the national-level percentage change in m from 2016 to 2018 applies in all provinces:

$$m_P^{2016} = m_P^{2018} / \%m$$

This implies:

$$X_{1,P}^{2016} + X_{4,P}^{2016} = \frac{m_P^{2016}}{m_P^{2016} + 1} X_{TOT,P}^{2016}$$

$$X_{2,P}^{2016} + X_{3,P}^{2016} = \frac{1}{m_P^{2016} + 1} X_{TOT,P}^{2016}$$

Using the national-level data, we calculate, for the year 2016, the ratio of production between categories 1 and 4 and the ratio of production between categories 2 and 3:

$$r_{14} = X_{1,N}^{2016} / X_{4,N}^{2016}$$

$$r_{23} = X_{2,N}^{2016} / X_{3,N}^{2016}$$

We assume that these national-level ratios across the categories apply at the provincial level. This enables us to obtain the provincial-level production levels in each of the four categories:

$$X_{1,P}^{2016} = \frac{r_{14}}{r_{14}+1}\left(X_{1,P}^{2016} + X_{4,P}^{2016}\right)$$

$$X_{4,P}^{2016} = \frac{1}{r_{14}+1}\left(X_{1,P}^{2016} + X_{4,P}^{2016}\right)$$

$$X_{2,P}^{2016} = \frac{r_{23}}{r_{23}+1}\left(X_{2,P}^{2016} + X_{3,P}^{2016}\right)$$

$$X_{3,P}^{2016} = \frac{1}{r_{23}+1}\left(X_{2,P}^{2016} + X_{3,P}^{2016}\right)$$

Appendix B: Determining Values and Distribution of Cost Function Parameters

We obtain parameters for the generators' cost functions in two steps. First, we calibrate all of the parameters for the cost function of the median-cost generator in each technology class. We then derive parameters that determine the distribution of the constant term for the family of cost functions of each technology class.

1. Parameters for Median Generator in Each Technology Class

For each of the 11 generator technologies, we specify the following functional form for the cost function:

$$C = \phi_0 + \phi_1 q^{\phi_2}$$

where ϕ_0, ϕ_1, and ϕ_2 are parameters. We impose the following two restrictions to identify the parameters for each generator technology.

1. At the benchmark level of output, q_0, the cost function yields the observed benchmark cost, C_0: $\phi_0 + \phi_1 q^{\phi_2} = C_0$.

2. At q_0, marginal production cost C' C' is equal to the benchmark market price of electricity p_0: $\phi_2 \phi_1 q^{\phi_2 - 1} = p_0$.

The two conditions together imply:

$$\phi_2 = \frac{p_0 q_0}{C_0 - \phi_0}$$

and

$$\phi_1 = (C_0 - \phi_0) q_0^{-\phi_2}$$

With three parameters and two identifying conditions, there is an infinite number of combinations of the parameters could meet the conditions. In particular, for any given choice of ϕ_0 there is a combination of ϕ_1 and ϕ_2 that meets the two conditions. We choose ϕ_0 so that, applying the two equations immediately above, it yields values of ϕ_1 and ϕ_2 that generate the desired target price elasticity of supply under business as usual. This cost function implies the following formula for the price elasticity of supply, η:

$$\eta = (\phi_2 \phi_1)^{1/(1-\phi_2)} \frac{1}{\phi_2 - 1} p^{1/(\phi_2 - 1)} / q$$

2. Distribution of Costs within Technology Classes

To incorporate cost heterogeneity within each technology class, we vary the parameter ϕ_0 that applies to each class. ϕ_0 is a constant term in the cost function for each class. We assume that this parameter is distributed according to a beta distribution. This is a bounded distribution. The probability density function (pdf) of beta distribution has the general form:

$$\frac{x^{\omega-1}(1-x)^{\delta-1}}{\int_0^1 v^{\omega-1}(1-v)^{\delta-1} dv}$$

We impose symmetry on this pdf by setting ω equal to δ.

a. Determining values for the maximal, minimal, and mean values of ϕ_0

For consistency with the data, we require that ϕ_{0mean} the mean value of ϕ_0 from the distribution, be equal to the value obtained in the calibration procedure above for the representative generator in the given technology class.

Economic considerations imply that the upper bound of the distribution should have a value that makes profit just equal to zero for the generator with that value in the baseline. The generator with $\phi_0=\phi_{0max}$ is a marginal producer. It makes zero economic profit and thus even a slight increase in cost implies negative profit and induces this unit to shut down. Thus ϕ_{0max} must have a value that makes profit equal to zero under business-as-usual (or baseline) conditions. Hence ϕ_{0max} satisfies:

$$p\,q_{BAU} + (\overline{p} - p)\overline{q}_{BAU} - \phi_{0\max} - \phi_1 q_{BAU}{}^{\phi 2} = 0$$

Hence,

$$\phi_{0max} = p q_{BAU} + (\overline{p} - p)\overline{q}_{BAU} - \phi_1 q_{BAU}{}^{\phi_2}$$

b. Translating the Beta Distribution into a Distribution for ϕ_0.

In its standard form, the beta distribution is defined over the interval (0,1). We need to shift and scale the standard distribution over the interval (0,1) translates to the interval (ϕ_{0min}, ϕ_{0max}) with mean value ϕ_{0mean}.

Let *a* and *b* denote the scale factor and the shift factors that translate the pdf's initial (0,1) distribution into the desired distribution for the model. And let *x* be the mean of the initial beta distribution. We choose *a* and *b* to satisfy:

$$\phi_0 = a(x - 0.5) + b$$

s.t.

when x = 0.5, $\phi_0 = \phi_{0mean}$

when x = 1, $\phi_0 = \phi_{0\max}$

The solution is: $a=2(\phi_{0max} - \phi_{0mean})$ and $b=\phi_{0mean}$. Under the TPS or cap and trade, there will exist values of ϕ_0 that are critical in the sense that any generator with ϕ_0 greater than that value will have zero profit. This translation enables us to determine the fraction of generators in the technology class involved that have ϕ_0 above this value, and thus the number of generators that must shut down. This enables us to calculate the loss of profits to the generators that shut down. In addition, from the distribution of costs for the generators that remain in operation, we can calculate the changes in profit to the remaining generators.

The calculations rely on the pdf and cumulative distribution functions defined on the distribution of ϕ_0. These distributions can be derived from the pdf for the x translation of ϕ_0. Because the translation is linear, the cdf for ϕ_0 is identical to the cdf for $x(\phi_0)$. The probability density functions $pdf_{\phi_0}\left(\phi_0\right)$ and $pdf_x\left(x\right)$ are not identical, however. The relationship between the two can be derived as follows. We start with the recognition that $cdf_{\phi_0}(\phi_0) = cdf_x(x)$. Then we take the full derivative with respect to x on both sides:

$$\frac{d}{d\phi_0} cdf_{\phi_0}(\phi_0) \frac{d\phi_0}{dx} dx = \frac{d}{dx} cdf_x(x) dx$$

$$pdf_{\phi_0}\left(\phi_0\right) \frac{d\phi_0}{dx} = pdf_x\left(x\right)$$

Since $\phi_0 = a(x - 0.5) + b$, we have $\frac{d\phi_0}{dx} = a$. As a result,

$$pdf_{\phi_0}(\phi_0) a = pdf_x(x)$$

or

$$pdf_{\phi_0}\left(\phi_0\right) = \frac{pdf_x\left(x\right)}{a}$$