Incidence, Environmental, and Welfare Effects of Distortionary Subsidies

Garth Heutel, David L. Kelly

Abstract: Government policies that are not intended to address environmental concerns can nonetheless distort prices and affect firms' emissions. We present an analytical general equilibrium model to study the effect of distortionary subsidies on factor prices, pollution, and welfare. Based on real-world policies, we model an output subsidy, a capital subsidy, relief from environmental regulation, and a minimum level of labor employment that firms must agree to in exchange for the subsidies. Each policy creates both output effects and substitution effects on input prices and emissions. We calibrate the model to the Chinese economy. Variation in production substitution elasticities does not substantially affect input prices, but it does substantially affect emissions. Distortionary subsidies can both raise emissions and decrease output. Therefore, reducing distortionary subsidies can reduce emissions without a trade-off in lost output. Such opportunities arise when the subsidized sector is moderate in size.

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NEARLY ALL GOVERNMENTS SUPPORT particular firms or sectors by granting low-interest financing, reduced regulation, tax relief, price supports, monopoly rights, and a variety of other subsidies. Subsidies are not lump sum, but instead introduce distortions by favoring particular firms, sectors, and/or inputs. This paper determines the incidence, environmental, and welfare effects of distortions induced by these subsidies, which are particularly common in environmentally sensitive industries.

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We present a two-sector general equilibrium model of an economy in which one sector receives subsidies and the other does not. Our motivating example is the Chinese economy, in which a large fraction of the economy is composed of state-owned enterprises (SOEs). We consider four different ways in which regulators interfere with the subsidized sector, based on observed policies in China. First, SOEs may have easier or cheaper access to capital or to loans, modeled here as an interest subsidy.[1] Second, SOEs may receive an output subsidy.[2] Third, SOEs may face less stringent environmental standards, modeled as a subsidy to an emissions tax.[3] Fourth, SOEs incur extra costs along with the subsidies. In particular, SOEs are subject to a requirement that employment must be greater than a minimum level.[4]

While our motivating example is the Chinese economy, our analytical model is general enough to apply to subsidies in other economies.[5] The model also applies to policies within a country targeted at a single industry. For instance, the US auto bailout in 2008–9 fits this model, since the subsidies implicit in the bailout were aimed only at some domestic, not foreign, manufacturers operating in the United States. Similarly, the airline industry could be modeled where the distinction between subsidized and nonsubsidized firms follows the distinction between legacy and low-cost carriers.[6]

Our subsidies differ from typical analysis of the incidence of subsidies or taxes in the literature in that only some firms receive subsidies. We find that subsidies tied to the use of a particular input (e.g., low interest loans, relief from environmental regulation) have three effects on factor prices and on emissions. First, subsidized firms tend to increase demand for the subsidized input at the expense of substitute inputs. This substitution effect increases economy-wide demand for the subsidized input. Second, the subsidized firm tends to produce more, increasing demand by the subsi-

1. Fisher-Vanden and Ho (2007) documents and studies substantial interest subsidies to Chinese industries, including energy-intensive industries.

2. Hsieh and Klenow (2009) model the Chinese economy where subsidies to output play a prominent role.

3. Dasgupta et al. (2001) show that Chinese SOEs have more bargaining power and are therefore their pollution is monitored less intensively.

4. Yin (2001) models overstaffing among Chinese SOEs and argues that overstaffing is widespread.

5. Bergoeing et al. (2002) study output and interest subsidies in Chile and Mexico. Barde and Honkatukia (2004) list subsidies among various OECD countries.

6. In the latter two examples, government subsidies took the form of government equity and debt financing at below market rates, which are interest subsidies in our framework. McNulty and Wisner (2014) and Shleifer and Vishny (1994) provide anecdotal evidence of overstaffing at firms receiving subsidies, and Faccio, Masulis, and McConnell (2006) and Jiang, Kim, and Zhang (2010) provide econometric evidence that firms with more employees are more likely to receive bailouts.

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dized firm for all inputs. This output effect is also created by output subsidies, though the substitution effect is not. The price of the subsidized input and complementary inputs increases at the expense of substitute inputs. Third, as input prices change, the private firms alter their input usage, usually in the opposite direction. Therefore, subsidies produce ambiguous and sometimes counterintuitive effects on total output and emissions. For example, if the subsidized sector is relatively large, then an interest subsidy has little effect on emissions in the subsidized sector: since the subsidized sector is already renting most of the capital, further increases in the demand for capital implies a large increase in the interest rate. The percentage increase in capital in the subsidized sector is small, but the percentage decrease in the private sector is large. Therefore, assuming the emissions input is complementary, the increase in subsidized emissions is more than offset by the decrease in private emissions.

Novel to our model, firms must use a minimum quantity of labor in exchange for receiving subsidies. Increasing the minimum labor constraint moves labor from the private to the subsidized sector. The demand for capital therefore increases in the subsidized sector but decreases in the private sector. The interest rate rises if the subsidized sector is more capital-intensive than the private sector.

We next turn to welfare analysis. An efficient equilibrium with two sectors equalizes marginal products. Input and output subsidies allocated to a single sector move inputs to the subsidized sector, which results in an inefficiency: because marginal products are diminishing, inputs moved to the subsidized sector are less productive than in the private sector. Therefore, subsidies can both decrease economy-wide output and increase economy-wide emissions. Output declines because inputs are concentrated in the less productive sector, and emissions increase because the subsidized sector substitutes emissions for other less-productive inputs. Therefore, we show that reducing subsidies can reduce emissions without the usual output loss trade-off. We prove that such welfare-enhancing opportunities exist when the subsidized sector is intermediate in size.[7] Intuitively, a decrease in subsidies will shift output from the subsidized to the private sector. If the subsidized sector is too small, then this will not generate a large enough change in factor prices needed to increase total output. Emissions will decrease in the subsidized sector and increase in the private sector; if the subsidized sector is too large, then the change in factor prices will be so large that total emissions will increase.[8]

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7. The upper and lower bounds are presented in the proposition proof in appendix A.VI.

8. Conceivably, this could be related to recent growth of Chinese output and emissions. China's SOEs were much larger in the 1980s and 1990s. When the subsidies began declining, we saw exactly what the model predicts: tremendous output growth in the private sector. Because the growth was so strong, pollution went up: the scale effect overwhelmed the fact that the private sector that replaced the SOEs was emitting less per unit of output. Now the

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An emissions tax falls more heavily on the subsidized sector, which uses more emissions per unit of output. Therefore, the emissions tax partially counteracts the advantage that subsidies provide. Indeed, we show that the optimal emissions tax in a second-best environment with a given level of distortionary subsidies exceeds the marginal damage (the Pigouvian tax). By causing output to shift away from the subsidized firm, the emissions tax partially neutralizes the adverse effects of the subsidies (concentrating inputs in the less productive subsidized sector).

A literature exists that studies tax incidence in general equilibrium in other contexts. For instance, Harberger (1962) also identifies how both factor intensities and substitution elasticities are key determinants of factor prices. Fullerton and Heutel (2007, 2010) extend this literature to consider pollution taxes and environmental mandates. The contributions of this paper relative to that literature are threefold. First, in addition to considering incidence effects (factor prices), we also examine two other issues: pollution effects and welfare implications. Second, rather than just economy-wide capital taxes, pollution taxes, or pollution standards, we model a wide range of policies targeted to individual sectors. Some of these policies are targeted to pollution, but most are not. However, all policies can have environmental effects. Third, we analyze the effects of the binding labor constraint faced by the subsidized firm, which must be satisfied in exchange for its subsidies. This is most relevant to our application to China but also applicable in other contexts as we discuss below.

To gauge the magnitude of the effects, we calibrate our model to the Chinese economy, where the distinction between subsidized and private firms is clear in our data. We simulate for base-case parameter values and conduct sensitivity analysis over the parameters describing each sector's substitution elasticities in production. One determinant of the incidence (the changes in factor prices) of the policies is the capital intensity of the subsidized sector. Our calibration indicates that the subsidized sector is relatively capital-intensive. Therefore in our simulations, subsidies hurt labor less than they help capital. This pattern is qualitatively unaffected by the substitution elasticity values. In contrast, the effects on emissions depend crucially on the substitution elasticity values. The greater the ability of one sector to substitute into emissions away from an alternate input whose price increases, the larger that sector's emissions increase.

Despite the prevalence of subsidies,[9] little is known about their general equilibrium effect on factor prices and the environment. Barde and Honkatukia (2004) discuss a

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SOEs are smaller; further reductions in subsidies will likely lead to smaller growth effects and decreases in pollution.

9. Brandt and Zhu (2000) report that subsidies in China amount to 6.8% of GDP in 1993. Further, van Beers and van den Bergh (2001) estimate worldwide subsidies are 3.6% of world GDP in the mid-1990s. Barde and Honkatukia (2004), report that agriculture, fishing,

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few channels by which subsidies may affect the quality of the environment. Still, their analysis is largely informal. Indeed, they note that "a thorough assessment would require a complex set of general equilibrium analysis (to evaluate the rebound effect on the economy)" (Barde and Honkatukia 2004, 268). This paper provides such a general equilibrium analysis, including all of the discussed channels.

Subsidies can be used to protect favored industries against foreign competition. Many trade agreements explicitly call for a reduction in subsidies. Bajona and Kelly (2012) examine the effect on the environment of eliminating the subsidies required for China to enter the World Trade Oraganization and find that elimination of subsidies reduces steady-state emissions of three of four pollutants studied. Van Beers and van den Bergh (2001) show how subsidies increase output and therefore emissions in a small open economy. In contrast, our results derive from general equilibrium effects of subsidies on domestic competitors.

In our model, input and output subsidies increase the share of output produced by subsidized firms. In the typical equilibrium, subsidies allow an overly large and unproductive subsidized sector to compete with the more productive private sector. A related literature considers competition between formal and informal sectors. In Bento, Jacobson, and Liu (2013), informal firms receive an effective subsidy by avoiding wage taxes but must use a technology that is only efficient if the firm remains small. The informal sector grows until the inefficiencies offset the tax benefits. While their model and ours have similar equilibrium structures, Bento et al. (2013) is concerned primarily with double dividend issues associated with replacing labor taxes with energy taxes. In contrast, our focus is on the incidence, environmental, and welfare effects of subsidies.[10]

Previous work has provided an important first step in identifying the extent of subsidies and likely channels by which they affect the environment. Still, the previous literature does not examine the incidence of subsidies, and most prior work looks at individual subsidies in partial equilibrium. An exception is Bajona and Kelly (2012), who provide a model where private and subsidized firms coexist. They prove the existence of a general equilibrium in which subsidized firms and private firms coexist with the share of production of subsidized firms determined endogenously by the subsidies, labor requirement, and technology difference. Bajona and Kelly (2012) consider only two kinds of subsidies, direct subsidies and interest subsidies. In addition to direct and interest subsidies, we consider also output subsidies and regulatory relief.

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energy (especially coal), manufacturing, transport, and water are all heavily subsidized, environmentally sensitive industries.

10. In addition, our model considers output and input subsidies and cash transfers, whereas their tax benefit is implicitly an output subsidy.

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More importantly, our framework considers an endogenous emissions input.[11] Because Bajona and Kelly (2012) effectively consider only a single endogenous capital input, only output effects exist, whereas in our framework substitution effects (substitution between emissions and capital) play a critical role.

1. MODEL

Here we briefly describe the model. More details are presented in appendix A.I. Consider a closed economy consisting of two representative firms producing an identical output good. Each firm has access to a production technology utilizing three inputs: capital, labor, and pollution. Production here is net of abatement costs, so higher pollution input means lower abatement costs, and therefore higher net production.[12] One firm is subsidized by the government, as described later; call its output level G (here we depart from Fullerton and Heutel [2007]). The other firm is nonsubsidized or private; call its output level P. The subsidized firm's production function is

$$G = A_G F(K_G, L_G, E_G),$$

where K_G, L_G, and E_G are the quantities of capital, labor, and pollution used by the subsidized firm, and A_G is total factor productivity (TFP). We assume F is a constant returns to scale function. Similarly,

$$P = A_P F(K_P, L_P, E_P),$$

with A_P, K_P, L_P, and E_P defined analogously. Henceforth, we normalize A_P to one.

Households supply $\bar{K}$ units of capital and $\bar{L}$ units of labor inelastically, allocated across the two sectors G and P. Equilibrium in the factor markets imply:

$$K_P + K_G = \bar{K},$$

$$L_P + L_G = \bar{L}.$$

We define λ_{ij} to be the fraction of the total supply of factor i that is employed by firm j (e.g., $\lambda_{KP} = K_P/\bar{K}$).

The private firm faces four prices, q_P, r, w, and τ, for output and inputs K_P, L_P, and E_P, respectively. Input prices equal marginal products:

$$r = q_P F_K(K_P, L_P, E_P),$$

$$w = q_P F_L(K_P, L_P, E_P),$$

11. Bajona and Kelly (2012) also focus on trade effects, whereas the focus of the current paper is on incidence.

12. See, e.g., Bartz and Kelly (2008) for a derivation of a production function with pollution as an input from abatement cost functions.

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$$\tau = q_P F_E(K_P, L_P, E_P).$$

The price of pollution τ is a government policy variable, while the prices of output, capital, and labor are endogenous. The firm's production decisions are characterized by its Allen elasticities of substitution (Allen 1938). The Allen elasticity $e_{P,ij}$ is positive when inputs i and j are substitutes and negative when they are complements. We will assume throughout that all inputs are substitutes for each other (the cross-price elasticities are positive). The own price Allen elasticity $e_{P,ii}$ is always negative. The parameters θ_{Pi} represent the share of total revenue spent on input i in sector P, for example, $\theta_{PK} \equiv rK_p/q_P P$. Constant returns to scale implies zero profits, so $\theta_{PK} + \theta_{PL} + \theta_{PE} = 1$. Constant returns to scale implies that the firm earns zero profits:

$$\pi_P = q_P P - rK_P - wL_P - \tau E_P = 0.$$

The subsidized firm's production is modeled analogously, although it faces different prices due to subsidies. We consider four types of subsidies, all of which are faced only by the subsidized (government) firm. All subsidies net of emissions tax revenue are financed via lump-sum taxes.

Capital Subsidy γ

First, the subsidized firm receives a discount on its capital costs. The discount may arise from the government guaranteeing repayment of funds borrowed by subsidized firms, direct loans from the government at reduced interest rates, state-owned enterprises borrowing at the government's rate of interest, or as the government steering deposits at state-owned banks to subsidized firms (common in developing countries) at reduced interest rates. Any of these implicit or explicit subsidies imply a lower effective rental price of capital for the subsidized firm, $r_G = (1 - \gamma)r$, where γ is the interest subsidy rate.

Output Subsidy ε

Second, the subsidized firm receives a subsidy of ε per unit of output. The output subsidy may also be interpreted as a price support that applies only to the subsidized firm (for example, the government buys excess demand above the market price from the subsidized firm and distributes the goods to households). If the consumer price of subsidized firm output is q_G, then the effective output price that the subsidized firm faces is $q_{GN} = (1 + \varepsilon)q_G$.

Pollution Tax Subsidy ϕ

Third, the government reduces the environmental regulatory burden the subsidized firm faces. In particular, the subsidized firm pays a pollution tax rate of $\tau_G = \tau(1 - \phi)$. Here $1 - \phi$ may also represent the fraction of emissions reported by the subsidized firm if, for example, the government monitors subsidized firms less often (Gupta and

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Saksena [2002] find that subsidized SOEs are monitored less often, and Wang et al. [2003] find that SOEs enjoy bargaining power over environmental compliance). As with Fisher-Vanden and Ho (2007), we are able to investigate how environmental regulations interact with other subsidies, like a capital subsidy. Input prices net of the subsidies equal marginal products for the subsidized firm:

$$r_G = q_{GN} A_G F_K(K_G, L_G, E_G),$$

$$w_G = q_{GN} A_G F_L(K_G, L_G, E_G),$$

$$\tau_G = q_{GN} A_G F_E(K_G, L_G, E_G).$$

Labor Constraint $\bar{L}_G$

Fourth, if subsidized and nonsubsidized firms coexist, some cost to receiving subsidies must exist. Following Bajona and Kelly (2012), we model this cost in a simple way. In particular, we assume that in order to receive subsidies, the government requires labor employment at the subsidized firm to be greater than or equal to $\bar{L}_G$ ($L_G \geq \bar{L}_G$).[13] The minimum labor constraint means the cost of receiving subsidies is a labor cost, which may include hiring lobbyists and/or hiring labor in key districts to increase bargaining power.[14] In exchange for employing $\bar{L}_G$, the government covers any losses through a direct subsidy (cash payment), S. The labor constraint binds if and only if the marginal product of labor in subsidized firms is below the wage rate, which causes subsidized firms to earn negative profits. Subsidized and private firms then coexist if subsidized firms receive a direct subsidy large enough for the subsidized firm's profits to be nonnegative, including the direct subsidy. Subsidized firm profits are then:

$$\pi_G = q_{GN} G - r_G K_G - w L_G - \tau_G E_G + S.$$

If the constraint does not bind, subsidized firms have a competitive advantage and will drive the private firms from the market. Since this case is less interesting, we consider only the case where the constraint binds. For the constraint to bind (that is, for the subsidized firm not to drive the private firm from the market), the subsidized

13. Note that the model is consistent either with the government imposing a minimum labor constraint as a condition for approval of a request for subsidies, or with the government exerting pressure on a firm to maintain a minimum quantity of labor, and then using subsidies to keep the firm in the market.

14. Shleifer and Vishny (1994) present a political economy model explaining why such labor constraints may arise in a bargaining process as a result of the subsidies modeled here. McNulty and Wisner (2014) note that GM was not allowed to close certain unprofitable factories in politically sensitive districts.

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firm must be less productive than the private firm ($A_G < 1$).[15] The labor constraint introduces a shadow price of labor for the subsidized firm, w_G, that differs from the market price w faced by the private firm.

A lump-sum tax finances all subsidies net of emissions tax revenue.[16] The government budget constraint is not needed since it determines the lump-sum tax, which does not affect any other decisions.

The two firms produce identical goods, so perfect competition implies that consumer prices are equal:

$$q_P = q_G.$$

We totally differentiate each of the equilibrium equations (two production equations, two zero profit conditions, six input demand equations yielding four independent equations, two equations that determine equilibrium input usage, three equations that define prices for the subsidized firm, the minimum labor constraint, and the equation equalizing the price faced by each firm). The model then consists of equations (A1) through (A15), presented in appendix A.I. These equations are linear in the differentiated variables, which we denote using a caret; for example, $\hat{r} \equiv (dr/r)$. The five exogenous policy variables are $\hat{\varepsilon}$, $\hat{\tau}$, $\hat{\phi}$, $\hat{\gamma}$, $\hat{\bar{L}}_G$. The 16 endogenous variables are: $\hat{K}_P$, $\hat{L}_P$, $\hat{K}_G$, $\hat{L}_G$, $\hat{r}$, $\hat{w}$, $\hat{q}_P$, $\hat{P}$, $\hat{q}_G$, $\hat{G}$, $\hat{r}_G$, $\hat{w}_G$, $\hat{\tau}_G$, $\hat{q}_{GN}$, $\hat{E}_G$, $\hat{E}_P$. The model does not determine the price level, so the solution requires a normalization. We normalize relative to the price of output by setting $\hat{q}_P = 0$. Now, the remaining 15 endogenous variables are the solution to the linear system of equations (A1)–(A15).

We solve the model through successive substitution. The steps of the solution method are available from the authors. We present the results in three parts. First, we present the incidence results, that is, the effect of policy changes on the returns to capital and to labor. Second, we present the emissions results. Finally (in section 4), we consider welfare implications.

2. INCIDENCE

We derive a closed-form solution for $\hat{r}$ and $\hat{w}$. However, here we present only the expression for $\hat{r}$. By subtracting equation (A6) from equation (A5) and invoking the normalization $\hat{q}_P = 0$, it can be shown that $\hat{w} = -(\theta_{PK}/\theta_{PL})\hat{r} - (\theta_{PE}/\theta_{PL})\hat{\tau}$. Thus, if the policy variable τ remains unchanged, then the sign of the change in the wage resulting from any other policy change is the opposite of the sign of the change in

15. In particular, $A_G < 1/(1+\varepsilon)$ is necessary for the constraint to bind. A sufficient condition for the constraint to bind is $A_G < \min(1-\gamma, 1-\phi)/(1+\varepsilon)$. For the case of Cobb-Douglas production, the constraint binds if and only if $A_G < (1-\gamma)^{\theta_K}(1-\phi)^{\theta_E}/(1+\varepsilon)$.

16. An interesting extension is to finance subsidies via non-lump-sum taxes, which would exacerbate the distortions already present.

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the rental rate. This does not mean that one factor gains and one loses, since both of these prices are relative to an arbitrary numeraire. Rather, if $\hat{r} > 0$ and $\hat{w} < 0$, then labor bears a disproportionately high share of the burden of the policy change relative to capital.[17]

Proposition 1: Suppose $A_G < \min(1-\gamma, 1-\phi)/(1+\varepsilon)$ and G and P are constant returns to scale. The solution for $\hat{r}$ is then:

$$\hat{r} = \frac{1}{D}\Big\{ -\theta_{GK}\lambda_{KG}(e_{G,KK} - 2e_{G,KL} + e_{G,LL})\hat{\gamma} + \lambda_{KG}(e_{G,KL} - e_{G,LL})\hat{\varepsilon} + -\theta_{GE}\lambda_{KG}B_G\hat{\phi} + \lambda_{KP}\left(\frac{\lambda_{KG}}{\lambda_{KP}} - \frac{\lambda_{LG}}{\lambda_{LP}}\right)\widehat{\bar{L}}_G + (\theta_{GE}\lambda_{KG}B_G + \theta_{PE}\lambda_{KP}B_P)\hat{\tau}\Big\}, \tag{1}$$

where

- $B_P \equiv e_{P,KE} - e_{P,EL} - e_{P,KL} + e_{P,LL}$
- $B_G \equiv e_{G,KE} - e_{G,EL} - e_{G,KL} + e_{G,LL}$, and
- $D \equiv -\lambda_{KG}\theta_{GK}(e_{G,KK} - 2e_{G,KL} + e_{G,LL}) - \theta_{PK}\lambda_{KP}(e_{P,KK} - 2e_{P,KL} + e_{P,LL}) > 0$.

Further,

a) $\frac{\partial\hat{r}}{\partial\hat{\gamma}} > 0$,
b) $\frac{\partial\hat{r}}{\partial\hat{\phi}} > 0$ if and only if $f_{KE} < 0$,
c) $\frac{\partial\hat{r}}{\partial\hat{\tau}} < 0$ if and only if $f_{KE} < 0$,
d) $\frac{\partial\hat{r}}{\partial\hat{\varepsilon}} > 0$,
e) $\frac{\partial\hat{r}}{\partial\widehat{\bar{L}}_G} > 0$ if and only if $\lambda_{KG}/\lambda_{KP} > \lambda_{LG}/\lambda_{LP}$.

Proof: see appendix A.II.

Given that D is positive, the coefficient on $\hat{\gamma}$ in the expression for $\hat{r}$ must be positive. An increase in γ, the subsidy to capital, increases the demand for capital by the subsidized firm, which pushes up the price of capital.[18]

The sign of the coefficient on $\hat{\phi}$ is opposite of the sign of B_G. We show in appendix A.III that $B_G < 0$ if and only if an increase in emissions reduces the marginal product of capital ($f_{KE} < 0$). Assume this condition holds, and it follows that the sign of the coefficient on $\hat{\phi}$ is positive. An increase in the emissions tax subsidy ϕ decreases the price of emissions for the subsidized firm. This creates an output effect

17. An alternative normalization assumption would be to set labor as the numeraire, so that the resulting change in r is relative to w. This is the normalization taken by Harberger (1962).

18. Since the supply of capital is fixed, the increase in capital in the subsidized firm replaces demand in the private firm through the higher interest rate.

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that expands production, increasing demand for capital and therefore its price. Only if capital and emissions are strong substitutes, so that $e_{P,KE}$ is positive and large enough to dominate the three other negative terms in B_P, does a substitution effect dominate, and an increase in the emissions tax subsidy reduces the demand for and price of capital. The coefficient on $\hat{\tau}$ is negative, since an increase in $\hat{\tau}$ increases the price of emissions.[19]

An increase in the output subsidy can be viewed as equivalently a decrease in the price paid by the subsidized firm for all three inputs. The coefficient on $\hat{\varepsilon}$ in equation (1) is positive. The increase in the output subsidy creates only an output effect, causing the subsidized firm to want to expand production. But because its labor input is fixed at $\bar{L}_G$, it can only expand by increasing its capital and emissions demand. This unambiguously raises the return to capital.

The coefficient on the labor constraint, $\widehat{\bar{L}}_G$, has the same sign as the expression $\lambda_{KG}/\lambda_{KP} - \lambda_{LG}/\lambda_{LP}$. This expression is positive when the subsidized firm is capital-intensive relative to the private firm; that is, when firm G has a higher capital-to-labor ratio than P. One might think that a tightening of the labor constraint must hurt labor, since it is forcing its quantity employed to be lower. However, there is a fixed labor stock, and any reduction in labor used in one firm is matched by an increase in labor in the other firm. Rather, a tightening of the labor constraint is a burden that falls only on the subsidized firm. If the subsidized firm is capital intensive, then that burden will fall harder on capital than on labor, and the price of capital falls.

One possible method for making the solution in equation (1) more interpretable is to consider special cases, which may isolate one effect among many. Following Fullerton and Heutel (2007), we consider two special cases. First, by assuming equal factor intensities in capital and labor across the two firms, we can eliminate output effects and focus solely on substitution effects.[20] Second, by assuming equal elasticities of factor demand across firms, we focus solely on output effects. We make this assumption by imposing a Cobb-Douglas structure on the production function for both firms. This assumption implies that all of the cross-price Allen elasticities are equal to one.[21] Further, the own-price elasticities satisfy $e_{M,ii} = [(\theta_{Mi} - 1)/\theta_{Mi}]$ for $M = G, P$

19. Technically, we assume that emissions and capital do not switch from being substitutes to complements or the reverse. If so, then it is possible that emissions and capital are substitutes for one firm, and complements for the other. In this case, a decrease in $\hat{\tau}$ may have a different effect than an increase in $\hat{\phi}$ as $\hat{\tau}$ directly affects emissions of both firms.

20. Equal factor intensities means that $K_G/K_P = L_G/L_P$, which implies that $\lambda_{KG}/\lambda_{KP} = \lambda_{LG}/\lambda_{LP}$.

21. An alternative and somewhat less restrictive assumption is merely to assume that all cross-price elasticities e_{ij} are equal to each other for each firm and are positive, and all own-price elasticities e_{ii} are equal to each other for each firm and are negative. This is the assumption

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and i = K, L, E. In addition, Cobb-Douglas production implies constant shares: $\theta_{Gi} = \theta_{Pi} = \theta_i$ for $i = K, L, E$.

The assumption of equal factor intensities does not substantially simplify the expression in equation (1). The exception is the effect of the labor constraint $\hat{\bar{L}}_G$ on the capital price; it completely disappears. This follows from the discussion above that the effect of $\hat{\bar{L}}_G$ on incidence is solely due to an output effect, not a substitution effect.

The assumption of Cobb-Douglas production simplifies the solution for the capital rental price (1) to:

$$\hat{r} = \lambda_{KG}\hat{\gamma} + \frac{\theta_L\lambda_{KG}}{(1-\theta_E)\theta_K}\hat{\varepsilon} + \frac{\theta_E\lambda_{KG}}{(1-\theta_E)}\hat{\phi} + \frac{\theta_L\lambda_{KP}}{1-\theta_E}\left(\frac{\lambda_{KG}}{\lambda_{KP}} - \frac{\lambda_{LG}}{\lambda_{LP}}\right)\hat{\bar{L}}_G - \left(\frac{\theta_E}{1-\theta_E}\right)\hat{\tau}. \quad (2)$$

As in the general case, with Cobb-Douglas production the capital subsidy increases demand for capital by the subsidized firm, which increases the interest rate. Similarly, the output subsidy creates an output effect which raises the demand for capital. The Cobb-Douglas specification implies that an increase in one input raises the marginal product of the other inputs; therefore the emissions tax reduces the interest rate, while the emissions subsidy increases the interest rate ($f_{KE} > 0$). Both of these are also output effects. As in the general case, an increase in the labor requirement increases the interest rate if and only if the subsidized firm has a greater capital to labor ratio than the private firm. For the Cobb-Douglas case, the difference in capital to labor ratios is positive if and only if:

$$A_G(1+\varepsilon) > (1-\phi)^{\theta_E}(1-\gamma)^{1-\theta_E}.$$

If the TFP difference is small, then so is the effective labor subsidy, which in turn implies the subsidized firm is less labor intensive. Similarly, large capital subsidies cause the subsidized firm to use more capital per unit of labor than the private firm.

Some of the simplifying assumptions of the model may be relaxed, resulting in solutions that are more complex but maintain the same interpretations. First, the two sectors produce identical goods (or perfect substitutes), and therefore the final goods prices must be equal in equilibrium. Because SOEs and private firms in China are competing against each other in the same markets, this assumption is relevant. Second, the labor constraint on the subsidized firm is relevant since overstaffing at SOEs is widespread (Yin 2001) in China. Relaxing the assumption of perfect substitutes, with or without the labor constraint creates a more complex solution with new incidence effects. The incidence effects we have identified remain, however, and the solution presented here arises as a limiting case as the elasticity of substitution becomes arbitrarily large. The details of these extensions are presented in appendix A.IV.

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imposed in Fullerton and Heutel (2007, case 4). However, in our model the results are slightly clearer with the stronger Cobb-Douglas assumption and no insights are sacrificed.

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3. EMISSIONS

Now we consider the effect on emissions in the private sector E_P. Instead of presenting a closed-form solution, it is more helpful to present an intermediate equation in the solution steps that expresses the change in emissions as a function of just the labor constraint, the emissions price, and the endogenous capital price:

$$\hat{E}_P = -\frac{\lambda_{LG}}{\lambda_{LP}}\widehat{\bar{L}}_G + \theta_{PE}(e_{P,EE} - 2e_{P,EL} + e_{P,LL})\hat{\tau} + \theta_{PK}B_P\hat{r}. \tag{3}$$

If $\bar{L}_G$ decreases, then more labor must be used in the private firm, and holding all else constant this increases the amount of emissions used in the private firm (from eq. [A4]). If the emissions price τ increases, then holding all else constant the emissions used in the private firm decreases. Finally, if the policy change is such that the price of capital increases, then the quantity of emissions used in the private sector decreases as long as $B_P < 0$. When capital and emissions are very substitutable, $B_P > 0$, the substitution effect from the capital price increase dominates, and emissions increases.

All of the effects on emissions in the private firm from any of the policy changes occur via their effect on r, as seen in equation (3), except for the additional effects from $\widehat{\bar{L}}_G$ and $\hat{\tau}$ (which also affect $\hat{r}$). The closed-form solution for $\hat{E}_P$ can be found by substituting equation (1) into equation (3). The results provide the same intuition as does equation (3). This solution is presented in tabular form in table 1 (along with the closed-form solution for $\hat{E}_G$, discussed below). For each row in table 1, the entry under the $\hat{E}_P$ column is the coefficient on that row's exogenous variable. For instance, the coefficient on $\hat{\gamma}$ in the closed-form expression for $\hat{E}_P$ is

$$-\frac{1}{D}\theta_{PK}B_P\theta_{GK}\lambda_{KG}(e_{G,KK} - 2e_{G,KL} + e_{G,LL}).$$

When $B_P < 0$, this coefficient is negative. An increase in γ increases r, which decreases E_P.

Table 1. Solution for $\hat{E}_P$ and $\hat{E}_G$

	$\hat{E}_P$	$\hat{E}_G$
$\hat{\gamma}$	$-\frac{1}{D}\theta_{PK}B_P\theta_{GK}\lambda_{KG}(e_{G,KK} - 2e_{G,KL} + e_{G,LL})$	$\theta_{GK}B_G + \theta_{GK}^2\left(-\frac{1}{D}\right)\lambda_{KG}(e_{G,KK} - 2e_{G,KL} + e_{G,LL})B_G$
$\hat{\phi}$	$-\frac{1}{D}\theta_{GE}\lambda_{KG}\theta_{PK}B_PB_G$	$\theta_{GE}(e_{G,EE} + e_{G,LL}) - \frac{1}{D}\theta_{GK}\theta_{GE}\lambda_{KG}B_G^2$
$\hat{\varepsilon}$	$\frac{1}{D}\lambda_{KG}\theta_{PK}(e_{G,KL} - e_{G,LL})B_P$	$(e_{G,EL} - e_{G,LL}) + \frac{1}{D}(\theta_{GK}B_G\lambda_{KG}(e_{G,KL} - e_{G,LL}))$
$\widehat{\bar{L}}_G$	$-\frac{\lambda_{LG}}{\lambda_{LP}} + \theta_{PK}B_P\frac{1}{D}\lambda_{KP}\left(\frac{\lambda_{KG}}{\lambda_{KP}} - \frac{\lambda_{LG}}{\lambda_{LP}}\right)$	$\frac{1}{D\lambda_{LP}}\{-\lambda_{LP}\lambda_{KP}\theta_{PK}(e_{P,KK} - 2e_{P,KL} + e_{P,LL}) + \theta_{GK}[\lambda_{KG}\lambda_{LP}(e_{G,KL} - e_{G,KK}) + \lambda_{KP}\lambda_{LG}(e_{G,KL} - e_{G,LL}) + (\lambda_{KG}\lambda_{LP} - \lambda_{LG}\lambda_{KP})(e_{G,KE} - e_{G,EL})]\}$
$\hat{\tau}$	$\theta_{PE}(e_{P,EE} - 2e_{P,EL} + e_{P,LL}) + \frac{1}{D}\theta_{PK}B_P(\theta_{GE}\lambda_{KG}B_G + \theta_{PE}\lambda_{KP}B_P)$	$\theta_{GE}(e_{G,EE} + e_{G,LL}) + \theta_{GK}B_G\frac{1}{D}(\theta_{GE}\lambda_{KG}B_G + \theta_{PE}\lambda_{KP}B_P)$

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The coefficients on $\hat{\overline{L}}_G$ and $\hat{\tau}$ include both the direct effect in the equation (3) and the indirect effects via the effects on $\hat{r}$ from equation (1).

An analogous expression for $\hat{E}_G$ is

$$\hat{E}_G = \hat{\overline{L}}_G + \theta_{GE}(e_{G,EE} + e_{G,LL})(\hat{\tau} - \hat{\phi}) + (e_{G,EL} - e_{G,LL})\hat{\varepsilon} + \theta_{GK} B_G(\hat{r} - \hat{\gamma}). \qquad (4)$$

The first term comes directly from equation (A8), where if nothing else changes, then the change in emissions equals the change in labor. The second term shows that the change in the net emissions price to the subsidized firm, $\hat{\tau} - \hat{\phi}$, negatively affects the emissions used by the subsidized firm. The third term demonstrates that in increase in the subsidized firm's output subsidy, ε, increases its use of the emissions input. Last, the final term is the effect of the change in the net price of capital to the subsidized firm, $\hat{r} - \hat{\gamma}$. It includes the endogenous $\hat{r}$. When the net price increases, the quantity of emissions used decreases, unless the substitution effect between capital and emissions dominates and $B_G > 0$.

As with equation (3), equation (4) is not a closed-form expression, but the closed-form solution can be found by substituting in equation (1). This is presented in the second column of table 1. Most of the resulting closed-form coefficients conform to the intuition presented by merely examining equation (4). For instance, the coefficient on $\hat{\varepsilon}$ in the closed-form expression for $\hat{E}_G$ is

$$(e_{G,EL} - e_{G,LL}) + \frac{1}{D}(\theta_{GK} B_G \lambda_{KG}(e_{G,KL} - e_{G,LL})).$$

The first two terms in the first set of parentheses are positive and represent the direct effect that can be seen in equation (4), and the rest of the terms are from the effect of $\hat{\varepsilon}$ on $\hat{r}$. Equation (1) shows that an increase in ε will increase r. Thus, combined with equation (4), as long as $B_G < 0$, this second term will be negative. In this case the direct effect from $\hat{\varepsilon}$ shown in equation (4) and the indirect effect via its effect on $\hat{r}$ move in opposite directions.

One other closed-form coefficient is worth discussing. The coefficient on $\hat{\overline{L}}_G$ in the expression for $\hat{E}_G$ is

$$\begin{aligned}\frac{1}{D\lambda_{LP}}\{&-\lambda_{LP}\lambda_{KP}\theta_{PK}(e_{P,KK} - 2e_{P,KL} + e_{P,LL}) \\ &+ \theta_{GK}[\lambda_{KG}\lambda_{LP}(e_{G,KL} - e_{G,KK}) + \lambda_{KP}\lambda_{LG}(e_{G,KL} - e_{G,LL}) \\ &+ (\lambda_{KG}\lambda_{LP} - \lambda_{LG}\lambda_{KP})(e_{G,KE} - e_{G,EL})]\}.\end{aligned}$$

All of the terms in this expression are positive, with the exception of the last line of the expression. The first part of the last line, $\lambda_{KG}\lambda_{LP} - \lambda_{LG}\lambda_{KP}$, is positive whenever the subsidized firm is capital intensive. The second part of the last line, $e_{G,KE} - e_{G,EL}$, is positive whenever capital is a better substitute for emissions than is labor, in the sub-

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sidized firm. Most of the coefficient is positive and picks up the fact that a reduction in $\bar{L}_G$ is a burden on the subsidized firm and causes it to contract, reducing its demand of input E_G. However, the firm can also substitute among its inputs. The subsidized firm could respond to its requirement to decrease labor demand (i.e., its increase in the shadow price of labor) by demanding more emissions or more capital. If it is capital intensive and if labor is a better substitute for emissions than is capital, then the increase in the shadow price will lead to a substitution effect that works to increase emissions in that sector. Even in this case, this effect will only dominate if it is larger than all of the other positive terms in the above coefficient.

We also examine the change in total emissions from both firms, $E = E_P + E_G$. The proportional change in emissions $\hat{E} = (E_P/E)\hat{E}_P + (E_G/E)\hat{E}_G$; that is, it is the sum of the two firms' proportional change in emissions, weighted by the share of total emissions for each firm. We present the expression for $\hat{E}$ in terms of the endogenous variable $\hat{r}$ rather than a closed-form solution to ease interpretation:

$$\begin{aligned}\hat{E} = {} & \left[\frac{E_P}{E}\left(-\frac{\lambda_{LG}}{\lambda_{LP}}\right) + \frac{E_G}{E}\right]\widehat{\bar{L}}_G + \left[\frac{E_P}{E}\theta_{PE}(e_{P,EE} - 2e_{P,EL} + e_{P,LL}) + \frac{E_G}{E}\theta_{GE}(e_{G,EE} + e_{G,LL})\right]\hat{\tau} \\ & + \left[\frac{E_G}{E}(-\theta_{GE})(e_{G,EE} + e_{G,LL})\right]\hat{\phi} + \left[\frac{E_G}{E}(e_{G,EL} - e_{G,LL})\right]\hat{\varepsilon} \qquad (5) \\ & + \left[\frac{E_G}{E}(-\theta_{GK})B_G\right]\hat{\gamma} + \left[\frac{E_P}{E}\theta_{PK}B_P + \frac{E_G}{E}\theta_{GK}B_G\right]\hat{r}.\end{aligned}$$

The first coefficient in this equation shows that the effect of $\widehat{\bar{L}}_G$ on $\hat{E}$ depends on both the factor shares of labor across the firms and on the allocation of emissions across the two firms. If the subsidized sector has a large share of total emissions, then this coefficient is likely to be positive, since an increase in the allowed labor in the subsidized sector will allow it to expand and demand more labor.

Every term in the coefficient on $\hat{\tau}$ in equation (5) is negative, since a higher emissions tax reduces emissions from both firms. Likewise, the coefficient on $\hat{\phi}$ is positive, since an increase in the emissions tax subsidy will reduce the subsidized firm's emissions. The coefficient on $\hat{\varepsilon}$ is positive, since an increase in the output subsidy to the subsidized firm will expand output and increase its demand for emissions. Finally, the coefficient on the capital subsidy $\hat{\gamma}$ in equation (5) is positive so long as $B_G < 0$; a higher subsidy encourages the subsidized firm to expand and therefore demand more emissions.

All of the aforementioned effects represent output effects, while all of the substitution effects are contained in the coefficient on $\hat{r}$. This coefficient is negative so long as B_G and B_P are both negative. If any exogenous policy changes ends up increasing the capital rental rate (relative to the numeraire), then the substitution effect will cause both firms to reduce emissions.

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The assumption of equal factor intensities does not substantially change the emissions results, with the exception of the coefficients on the labor constraint $\hat{\bar{L}}_G$. Its coefficient in the expression for $\hat{E}_P$ is

$$\lambda_{KP}^2\theta_{PK}[\lambda_{LG}(e_{P,KK} - 2e_{P,KL} + e_{P,LL}) + \lambda_{LP}\lambda_{LP}\lambda_{KG}(B_P - B_G)].$$

The first half of this expression in the square brackets is negative. When the labor constraint in the subsidized firm is tightened ($\hat{\bar{L}}_G > 0$), more labor is forced into the private firm, causing it to substitute away from emissions via a substitution effect. The second half of the expression in the brackets ($\lambda_{LP}\lambda_{LP}\lambda_{KG}(B_P - B_G)$) has the same sign as $B_P - B_G$. This is positive when the subsidized firm is more able to substitute among its inputs than is the private firm. If so the tightening of the labor constraint increases emissions in the private firm via this effect. The coefficient on the labor constraint in the expression for $\hat{E}_G$ is

$$\frac{1}{D}[-\lambda_{KP}\theta_{PK}(e_{P,KK} - 2e_{P,KL} + e_{P,LL}) - \theta_{GK}\lambda_{KG}(e_{G,KL} - 2e_{G,KL} + e_{G,LL})].$$

Under the equal factor intensity assumption, the final set of terms from the general solution of this coefficient in table 1 ($(\lambda_{KG}\lambda_{LP} - \lambda_{LG}\lambda_{KP})(e_{G,KE} - e_{G,EL})$) has disappeared. What is left is strictly positive. A tightening of the labor constraint causes the subsidized firm to expand, increasing its emissions.

Proposition 2: Let the assumptions of proposition 1 hold. Then the full solution for $\hat{E}_P$, $\hat{E}_G$, and $\hat{E} = \lambda_{EG}\hat{E}_G + (1-\lambda_{EG})\hat{E}_p$ in the case of Cobb-Douglas production is:

$$\begin{aligned}\hat{E}_G = {} & \frac{\theta_K}{\theta_L}\lambda_{KP}\hat{\gamma} + \frac{\theta_L + \theta_K\theta_E\lambda_{KP}}{(1-\theta_E)\theta_L}\hat{\phi} + \left(\frac{1}{\theta_L} - \frac{\lambda_{KG}}{(1-\theta_E)}\right)\hat{\varepsilon} - \frac{1}{(1-\theta_E)}\hat{\tau} \\ & + \left(1 - \frac{\theta_K\lambda_{KP}}{(1-\theta_E)}\left(\frac{\lambda_{KG}}{\lambda_{KP}} - \frac{\lambda_{LG}}{\lambda_{LP}}\right)\right)\hat{\bar{L}}_G,\end{aligned} \tag{6}$$

$$\hat{E}_P = -\frac{\theta_K}{\theta_L}\lambda_{KG}\hat{\gamma} - \frac{\theta_K\theta_E\lambda_{KG}}{(1-\theta_E)\theta_L}\hat{\phi} - \frac{\lambda_{KG}}{(1-\theta_E)}\hat{\varepsilon} - \frac{1}{(1-\theta_E)}\hat{\tau} - \left(\frac{\lambda_{LG}}{\lambda_{LP}} - \frac{\theta_K\lambda_{KP}}{1-\theta_E}\left(\frac{\lambda_{KG}}{\lambda_{KP}} - \frac{\lambda_{LG}}{\lambda_{LP}}\right)\right)\hat{\bar{L}}_G, \tag{7}$$

$$\begin{aligned}\hat{E} = {} & \frac{\theta_K}{\theta_L}(\lambda_{EG} - \lambda_{KG})\hat{\gamma} + \frac{\theta_L\lambda_{EG} + \theta_K\theta_E(\lambda_{EG} - \lambda_{KG})}{(1-\theta_E)\theta_L}\hat{\phi} + \left(\frac{\lambda_{EG}}{\theta_L} - \frac{\lambda_{KG}}{(1-\theta_E)}\right)\hat{\varepsilon} - \frac{1}{(1-\theta_E)}\hat{\tau} \\ & + \left(\lambda_{EP}\left(\frac{\lambda_{EG}}{\lambda_{EP}} - \frac{\lambda_{LG}}{\lambda_{LP}}\right) - \frac{\theta_K\lambda_{KP}}{(1-\theta_E)}\left(\frac{\lambda_{KG}}{\lambda_{KP}} + \frac{\lambda_{LG}}{\lambda_{LP}}\right)\right)\hat{\bar{L}}_G.\end{aligned} \tag{8}$$

Further:

a) $\frac{\partial\hat{E}_G}{\partial\hat{\tau}} < 0$, $\frac{\partial\hat{E}_P}{\partial\hat{\tau}} < 0$, and $\frac{\partial\hat{E}}{\partial\hat{\tau}} < 0$,
b) $\frac{\partial\hat{E}_G}{\partial\hat{\phi}} > 0$ and $\frac{\partial\hat{E}_P}{\partial\hat{\phi}} < 0$,
c) $\frac{\partial\hat{E}_G}{\partial\hat{\gamma}} > 0$, $\frac{\partial\hat{E}_P}{\partial\hat{\gamma}} < 0$, and $\frac{\partial\hat{E}}{\partial\hat{\gamma}} > 0$ if and only if $\phi > \gamma$.

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See appendix A.V. As with the general case, emissions of both firms and total emissions are decreasing in the emissions tax. Private emissions decrease with the emissions subsidy, while subsidized emissions increase, as output moves from the private to the subsidized sector through an increase in the demand for capital by the subsidized firm which raises the interest rate. The subsidized firm also directly increases emissions in response to lower emissions costs. The effect on total emissions is ambiguous: if the subsidized sector uses a large share of the capital and/or accounts for a relatively small share of emissions, then the decrease in emissions in the private firm outweighs the increase in the subsidized firm and an increase in the emissions subsidy could counterintuitively decrease emissions. If the subsidized sector accounts for a relatively small share of emissions the increase in subsidized emissions is small relative to the total emissions, and if subsidized sector uses most of the capital the emissions subsidy causes a relatively large increase in interest rates which decreases private emissions.

Indeed, the size of the subsidized sector (defined here by the size of the capital stock, that is, the book value of the firm) plays a critical role here in determining whether or not changes in all distortionary subsidies increase total emissions. Counterintuitively, a relatively small subsidized sector implies that subsidies tend to increase total emissions. To understand this result, consider an increase in the capital subsidy, which increases subsidized emissions through a direct output effect caused by a change in the price of capital. In addition, the increase in demand for capital by the subsidized firm raises the interest rate, causing an indirect effect which decreases emissions at both firms. If the subsidized sector is relatively large, then the increase in the demand for capital will have a relatively large effect on the interest rate, strengthening the indirect effect. When the subsidized sector is already large, increasing the capital subsidy has little effect on the subsidized sector: it already rents most of the capital and has difficulty obtaining more without a large increase in the interest rate, which causes emissions at the private firm to drop. Notice that as $\lambda_{KG} \rightarrow 1$ the increase in emissions in the subsidized sector goes to zero as the subsidized sector is unable to obtain more capital.

Whether or not capital and output subsidies increase emissions also depends on the share of capital and emissions used by the subsidized sector. The subsidized sector uses a larger share of emissions than of capital if and only if the emissions subsidy is larger than the capital subsidy, $\phi > \gamma$.[22] Therefore, capital subsidies increase emissions if and only if $\phi > \gamma$.

Equations (6)–(8) have important implications for environmental policy. The typical focus in environmental policy is on environmental regulation, here the emissions

22. It is straightforward to solve for the shares λ_{EG} and λ_{KG}. The solutions imply $\lambda_{EG} > \lambda_{KG}$ if and only if emissions are more subsidized than capital, $\phi > \gamma$.

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tax. But equations (6)–(8) show that policy makers can also substantially affect emissions by reducing distortionary subsidies. In general, input subsidies will have a large effect on emissions when the capital share of the subsidized sector is relatively large. Consider for example, the electric utilities industry. Data in Cao et al. (2009) imply that the capital share is $\theta_K = 0.72$ in the year 2000 for China.[23] Assuming an emissions share of 0.2,[24] and a small difference between the subsidized share of emissions and capital ($\lambda_{EG} = 0.25$ and $\lambda_{KG} = 0.2$) reducing the output subsidy by 10% has 2.3 times as large an effect on emissions as increasing the emissions tax by 10%. Reducing the capital subsidy by 10% has a larger effect on emissions than increasing the emission tax by 10% whenever $\lambda_{EG} - \lambda_{KG} > 0.15$.

4. WELFARE ANALYSIS

4.1. Preference-Independent Pareto-Improving Policies

Environmental policy trades off the environmental damages of pollution emissions with the output costs of reducing emissions. The presence of distortionary subsidies, however, creates a rare opportunity to both reduce emissions and increases total output, creating an unambiguous welfare gain, which we define as a "preference-independent Pareto improvement."[25]

Definition 1. A Preference-Independent Pareto-Improving Policy is a change in a policy variable that increases welfare regardless of the relative weight of consumption and emissions in the utility function. That is, it both increases output and reduces emissions.

In this section we consider the Cobb-Douglas special case, for which total output, $\hat{Y} = \lambda_{YG}\hat{G} + (1 - \lambda_{YG})\hat{P}$, is:

23. Cao et al. (2009) does not distinguish between SOEs and private firms (and thus just provides an aggregate factor share θ_K). Dissou and Siddiqui (2014) estimate $\theta_K = 0.728$ for the electric utilities industry in Canada.

24. Fullerton and Heutel (2007) consider examples with an emissions share of 0.25.

25. Our model has only a single good and homogeneous households. With heterogeneous goods and households, changes in prices across sectors could make some households worse off, even if total output rises and pollution falls. Subsidies are sometimes employed to allow otherwise inefficient firms to remain in the market. Since the direct subsidy adjusts in response to changes in the other subsidies, reducing subsidies does not result in unemployment costs. The experiment considered here is thus a reallocation of subsidies from input/output specific subsidies to direct subsidies. Finally, subsidies affect wages and the return to capital differently. Although homogeneous households see an unambiguous increase in income when output rises, if households are heterogeneous in terms of capital ownership and labor supply, some households may experience a decrease in income.

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$$\begin{aligned}\hat{Y} = {} & \frac{\theta_K}{\theta_L}(\lambda_{YG} - \lambda_{KG})\hat{\gamma} + \frac{\theta_E((1-\theta_E)\lambda_{YG} - \theta_K\lambda_{KG})}{(1-\theta_E)\theta_L}\hat{\phi} + \left(\frac{1-\theta_L}{\theta_L}\lambda_{YG} - \frac{\lambda_{KG}}{(1-\theta_E)}\right)\hat{\varepsilon} \\ & - \frac{\theta_E}{(1-\theta_E)}\hat{\tau} + \left(\lambda_{YP}\left(\frac{\lambda_{YG}}{\lambda_{YP}} - \frac{\lambda_{LG}}{\lambda_{LP}}\right) - \frac{\theta_K\lambda_{KP}}{(1-\theta_E)}\left(\frac{\lambda_{KG}}{\lambda_{KP}} + \frac{\lambda_{LG}}{\lambda_{LP}}\right)\right)\widehat{\bar{L}}_G.\end{aligned} \tag{9}$$

Equations (8) and (9) then imply:

Proposition 3: Suppose the assumptions of proposition 1 hold and the production technology is Cobb-Douglas. Then:

a) There exist regions $\lambda_{KG}^{\min,i} \le \lambda_{KG} \le \lambda_{KG}^{\max,i}$ for $i = \gamma, \phi, \varepsilon, L_G$ such that a decrease in γ, ϕ, ε, or L_G is a preference-independent Pareto-improving policy.

b) Increasing τ is never a preference-independent Pareto-improving policy.

Appendix A.VI contains the proof of proposition 3 and calculates the upper and lower bounds $\lambda_{KG}^{\min,i}$ and $\lambda_{KG}^{\max,i}$. The conditions require that the subsidies cause an increase in the interest rate large enough so that output falls, but not so large that the subsidies have a negative effect on emissions. As discussed above, the interest rate effect is large when the subsidized sector is large because the interest rate must increase relatively more with the subsidies when the subsidized sector is already renting most of the capital. Therefore, the lower bound $\lambda_{KG}^{\min,i}$ represents the minimum size of the subsidized sector such that a decrease in subsidies causes a large enough decrease in interest rates so that output increases. The upper bound $\lambda_{KG}^{\max,i}$ ensures that the decrease in interest rates is not so large that emissions also increase.

From equations (8) and (9), increasing the emissions tax always decreases emissions but always decreases output. The emissions tax increases costs at both firms and therefore causes an unambiguous decrease in output. Therefore, changing the emissions tax always involves a trade-off and is never a preference-independent Pareto-improving policy. For some parameter values, reducing subsidies can cause a larger reduction in emissions than raising emissions taxes and can also increase output. Thus, for such parameter values reducing subsidies yields unambiguously larger welfare gains than increasing the emissions tax.

Some policies may cause output and emissions to move in the same direction yet still increase welfare, depending on the relative strength of preferences for the environment versus consumption. Suppose now that the utility function $U[C, E]$ represents preferences, where C is consumption, utility is increasing and concave in C and decreasing in E, and in equilibrium $C = Y = G + P$. Then any policy change is Pareto-improving if and only if $\hat{Y} - \sigma\hat{E} > 0$, where $\sigma = -U_E[C, E]E/U_c[C, E]C$ is the elasticity of substitution between consumption and emissions. For this less re-

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strictive definition of Pareto-improving policies, the range of parameters $\lambda_{KG}^{\max,i} - \lambda_{KG}^{\min,i}$ increases for all $i \in \{\gamma, \phi, \varepsilon, L_G\}$, with either $\lambda_{KG}^{\max,i} = 1$ or $\lambda_{KG}^{\min,i} = 0$.

Proposition 3 may be extended to the case where the goods are not perfect substitutes and the labor constraint is not present. In this case, if we restrict the utility function to the constant elasticity of substitution (CES) class, then parameter ranges exist such that decreasing the emissions or output subsidies are preference-independent Pareto-improving policies. For example, if $\phi > \gamma$, then decreasing emissions or output subsidies cause production of the private goods to increase enough to more than offset the decrease in production of the subsidized good, while decreasing total emissions, regardless of the parameters of the CES utility function.

4.2. Optimal Emissions Tax

To this point, the model has taken the emissions tax and all of the subsidies as given. In our second-best environment with the distortionary subsidies, the government is unable to achieve the first best, so it is reasonable to assume a given emissions tax that is not necessarily optimal. Nonetheless, conditional on the level of the other subsidies, the emissions tax can be chosen to maximize welfare.

We assume that a social planner maximizes a welfare function $U[C, E]$, subject to a resource constraint $C = Y = G + P$. Here E, G, and P are functions of the subsidies and emissions tax, as in the previous sections. We then have:

Proposition 4: Suppose the assumptions of proposition 1 hold and the production technology is Cobb-Douglas. Then the optimal second-best emissions tax taking subsidies as given is:

$$\tau^* = \left(\frac{(1+\varepsilon)[(1-\gamma)\lambda_{KG} + (1-\phi)\lambda_{KP}]}{(1-\phi)((1-\gamma)\lambda_{KG} + (1+\varepsilon)\lambda_{KP})}\right)\left(\frac{-U_E[C,E]}{U_c[C,E]}\right).$$

Further, if either $\varepsilon > 0$ or $\phi > 0$ then $\tau^* > -U_E/U_c$.

The proof is in appendix A.VII. The optimal emissions tax is proportional to the marginal damages in consumption units $(-U_E/U_c)$, and that proportion is greater than one for any positive level of output or emissions subsidies.[26] The optimal tax is greater than the Pigouvian level. The subsidies concentrate emissions and capital inputs in the subsidized sector. Since the minimum labor constraint binds, the subsidized firm would like to use less labor. Although subsidies in general increase demand for labor by the subsidized firm, the increase is not enough to cause the labor constraint to cease to bind.[27] As subsidies increase, the labor input remains fixed at the

26. Note that λ_{KG} and λ_{KP} depend on all subsidies and the labor requirement.

27. If subsidies are sufficiently large, the labor constraint no longer binds and only the subsidized firm produces. We do not study this trivial case as our interest is in the (empirically relevant) case of competition between subsidized and private firms.

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minimum level and the emissions and capital inputs increase, causing diminishing returns. Diminishing returns then implies more emissions input per unit of output. Hence, the tax falls more heavily on the subsidized firm. Therefore, the regulator can increase the market share of the private firm by increasing the emissions tax, which is optimal because the private firm uses a more efficient technology. Therefore the emissions tax promotes the adoption of the more efficient technology.

Other models containing preexisting distortions (for instance, labor taxes) also find that the optimal emissions tax may differ from the marginal damages, for different reasons. For example, Bovenberg and Goulder (1996) find that the optimal emissions tax is less than the marginal damages due to an interaction effect in which the tax reduces labor supply. Conversely, Liu (2013) finds that the optimal emissions tax is above the marginal damages, since emissions taxes are less subject to tax evasion. Here we have a new channel: the emissions tax is above the marginal damages because the tax falls more heavily on the inefficient firm, which causes the firm with higher TFP to gain a larger share of production.[28]

5. NUMERICAL RESULTS

5.1. Calibration

We calibrate the model to investigate the magnitude of the effects found from the analytical solutions. China provides an ideal setting for calibrating a model in which some firms receive subsidies. State-owned enterprises (SOEs) in China are heavily subsidized.[29] The 2006 China Statistical Yearbook provides data on capital and labor inputs, profits, and emissions separately for state-owned enterprises and private firms (except emissions). An important component of the reform of the Chinese economy over the past several decades has been to allow private firms to compete with SOEs. Since SOEs are more pollution intensive than private firms, understanding the growth in the private sector relative to the state-owned sector has important implications for understanding how emissions evolve over time.[30]

We consider the SOEs to be the subsidized sector and the non-SOEs to be the private sector. Table 2 gives some summary statistics for SOEs and private firms in China from Bajona and Kelly (2012). The subsidized sector in China produces a nontrivial 47% share of output, but not so large as to invalidate the assumption of

28. Our model ignores the distortionary cost of funding the subsidies. Adding a requirement that the subsidies must be funded by distortionary labor or income taxes would complicate the calculation of the optimal emissions tax. It is unclear how the addition of revenue-recycling effects and tax-interaction effects would affect the optimal emissions tax.

29. Bajona and Kelly (2012), Brandt and Zhu (2000), Fisher-Vanden and Ho (2007), and Hsieh and Klenow (2009) all document various subsidies received by Chinese SOEs. Yin (2001) shows that SOEs in China hire excess labor.

30. China's strategy of allowing private firms to compete with SOEs differs from reforms in Russia and Eastern Europe, which emphasized privatization of SOEs.

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Table 2. Characteristics of SOEs in China by Industry, 1997

Industry	SOE Share of Value Added: $G/(G+P)$	Difference in Emissions Intensity: $\frac{E_G}{G}-\frac{E_P}{P}$	TFP Difference: A_G/A_P
Mining and Quarrying	.81	.46	.54
Textiles, Sewing, Leather, and Fur Products	.20	.58	.42
Other Manufacturing	.22	.56	.44
Production and Supply of Electric Power, Steam, and Hot Water	.75	.44	.78
Coking and Petroleum Refining	.81	.17	.77
Chemical Industry	.34	.32	.55
Building Materials and Nonmetal Mineral Products	.28	.40	.38
Metal Products	.54	.24	.65
Machinery and Equipment	.36	.46	.51
All Industry	.47	.42	.64

Note.—Data are from Bajona and Kelly (2012). The first column uses the 1998 China Statistical Yearbook, tables 13.11–13.12. The second column is table 2 of Bajona and Kelly (2012), with units equal to tons per 10K 1990 Yuan. The difference in emissions intensities is estimates using data from 1995 to 2007. The third column is from table 2 of Bajona and Kelly (2012).

perfect competition (across industries, the maximum SOE share is 81%). Column 3 of table 2 shows that TFP at Chinese SOEs is only 64% of private firms overall, and that SOEs have lower TFP across a broad range of industries. Column 2 of table 2 shows that SOEs are significantly more emissions intensive, which indicates that subsidies are likely to have important effects on economy-wide emissions.

The data give the value of capital and labor inputs in both sectors, which we use to directly calculate the input shares λ_{KP}, and so forth. We chose sulfur dioxide as the pollutant. Appendix A.VIII shows that a calibration with chemical oxygen demand yields almost identical parameter values. Calibration of other parameters, including the expenditure share parameters θ_{ij}, is described in appendix A.VIII.

The most difficult parameters to calibrate in our simulations are the Allen elasticities of substitution in each sector; they are not provided in the China Statistical Yearbook. In fact, we know of no reliable estimate of these parameters for China, presented separately for SOEs and private firms. Much of the previous literature has found evidence that capital is a slightly better substitute for pollution than is labor.[31]

31. Intuitively, when pollution reductions are required, new capital is installed, and thus capital and pollution are substitutes.

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For instance, de Mooij and Bovenberg (1998) report this (using energy inputs as a proxy for pollution) based on a synthesis of several earlier studies from Western European economies. Considine and Larson (2006) also find this result in estimates from electric power plants participating in the United States acid rain emissions permit program.[32] Lu and Zhou (2009) look specifically at China, and like de Mooij and Bovenberg (1998) they report elasticities with respect to energy rather than pollution. They find some evidence that labor is a better substitute for energy than is capital, and even that capital and energy may be complements during some years. However, their estimates vary substantially across years (see their fig. 2), and they do not differentiate between private firms and SOEs.

Because of the lack of reliable estimates of these substitution elasticities, we conduct sensitivity analyses over their values. We begin by using the same elasticity values as in Fullerton and Heutel (2010), in which capital is a slightly better substitute for pollution than is labor. Next, we use elasticity values derived from the results reported in Lu and Zhou (2009), in which labor is a better substitute for pollution than is capital.[33] In each case, the cross-price Allen elasticities are identical across the two sectors, but because of the different expenditure shares across sectors the own-price elasticities are not identical across sectors. We then consider cases in which the elasticities differ between the two sectors.

Table 3 summarizes the calibrated parameter values (the own-price elasticities are not presented but are derived from the rest of the parameter values). The subsidized sector is relatively capital intensive $((\lambda_{KG}/\lambda_{LG}) > (\lambda_{KP}/\lambda_{LP}))$. The share of expenditures that goes toward pollution taxes in both industries (θ_{GE} and θ_{PE}) is very small.

5.2. Simulations

We simulate four different exogenous policy changes. First, $\hat{\gamma} = 10\%$, simulating an increase in the capital subsidy rate to the subsidized firm. Second, $\hat{\varepsilon} = 10\%$, simulating an increase in the output subsidy rate to the subsidized firm. Third, $\hat{\phi} = 10\%$, simulating an increase in the pollution tax subsidy rate to the subsidized firm. Last, $\widehat{L}_G = 10\%$, simulating an increase in the minimum labor constraint faced by the subsidized firm (this last policy increase is a burden on the subsidized firm, while the other three policy simulations are a benefit to the subsidized firm, although the di-

32. See de Mooij and Bovenberg (1998, table 6.1) and Considine and Larson (2006, table 6). Note that these papers use alternative definitions of demand elasticities.

33. Lu and Zhou (2009) estimate input demand cross-price elasticities, but Allen elasticities can be calculated from those by dividing through by factor cost shares. They report factor shares (for capital, labor, and energy) for each year from 1978 to 2005; we take the mean across years. Input demand cross-price elasticities are reported between capital and energy (about zero) and between labor and energy (about 0.2). From these values we calculate $e_{KE} = 0$ and $e_{LE} = 0.74$. The cross-price elasticity between capital and labor is not reported, so we use the same base case value of $e_{KL} = 0.5$.

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Table 3. Calibrated Parameters

Parameter	Value
λ_{KP}	.4166
λ_{LP}	.7281
λ_{KG}	.5834
λ_{LG}	.2719
θ_{PK}	.2986
θ_{PL}	.7012
θ_{PE}	.0002
θ_{GK}	.1795
θ_{GL}	.8202
θ_{GE}	.0002
$e_{P,KL}$	.5
$e_{P,KE}$	.5
$e_{P,EL}$	.3
$e_{G,KL}$	.5
$e_{G,KE}$	.5
$e_{G,EL}$	.3
E_G/E	.75
γ	.57
ε	0
ϕ	.8

Note.—Calibrated parameters use sulfur dioxide emissions as a measure of pollution. Parameters using chemical oxygen demand are very similar. See appendix A.VIII for details of the calibration.

rect subsidy S will in equilibrium decrease to leave the subsidized firm's profits unchanged).[34] Panels B and C of table 4 report the results from these four policy changes. Row 1 in each of those panels represents the simulations using the base case parameter values; rows 2 through 4 represent sensitivity analysis over the elasticity parameters (see panel A).

5.2.1. *Base Case Incidence Results*

Focusing first on the base case simulations, the effect of either the capital subsidy ($\hat{\gamma}$) or the output subsidy ($\hat{\varepsilon}$) on incidence ($\hat{r}$ and $\hat{w}$) is identical up to two decimal

34. Note that since $\hat{\gamma} \equiv d\gamma/(1-\gamma)$, $\hat{\gamma} = 10\%$ corresponds to an increase in γ equal to $d\gamma = 0.10 \cdot (1-\gamma) = 0.043 = 7.5\%$. Similarly, the increase in $\hat{\varepsilon}$ is 0.1 and the increase in $\hat{\phi}$ is 0.02 or 2.5%. By equalizing the percent changes in subsidies, the exercise compares the elasticity of pollution and factor prices with respect to subsidies.

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Table 4. Simulation

A. Parameter Values

	$e_{P,KE}$	$e_{P,EL}$	$e_{G,KE}$	$e_{G,EL}$
1 (base case)	.5	.3	.5	.3
2	0	.74	0	.74
3	.5	.3	0	.74
4	0	.74	.5	.3

B. Simulation Results

	$\hat{\gamma}$ = 10%				$\hat{\varepsilon}$ = 10%			
	$\hat{r}$	$\hat{w}$	$\hat{E}_P$	$\hat{E}_G$	$\hat{r}$	$\hat{w}$	$\hat{E}_P$	$\hat{E}_G$
1	5.45%	−2.32%	−.83%	.33%	5.45%	−2.32%	−.83%	3.69%
2	5.45%	−2.32%	−2.36%	1.10%	5.45%	−2.32%	−2.37%	7.18%
3	5.45%	−2.32%	−.83%	1.10%	5.45%	−2.32%	−.83%	7.18%
4	5.45%	−2.32%	−2.36%	.33%	5.45%	−2.32%	−2.36%	3.69%

C. Simulation Results

	$\hat{\phi}$ = 10%				$\hat{\bar{L}}_G$ = 10%			
	$\hat{r}$	$\hat{w}$	$\hat{E}_P$	$\hat{E}_G$	$\hat{r}$	$\hat{w}$	$\hat{E}_P$	$\hat{E}_G$
1	.00%	.00%	.00%	3.36%	6.56%	−2.79%	−4.74%	9.52%
2	.00%	.00%	.00%	6.07%	6.56%	−2.79%	−6.58%	8.41%
3	.00%	.00%	.00%	6.07%	6.56%	−2.79%	−4.74%	8.41%
4	.00%	.00%	.00%	3.36%	6.56%	−2.79%	−6.58%	9.52%

D. Simulation Results

	$\hat{\gamma}$ = 10%		$\hat{\varepsilon}$ = 10%		$\hat{\phi}$ = 10%		$\hat{\bar{L}}_G$ = 10%		$\hat{\tau}$ = 10%	
	$\hat{E}$	$\hat{Y}$	$\hat{E}$	$\hat{Y}$	$\hat{E}$	$\hat{Y}$	$\hat{E}$	$\hat{Y}$	$\hat{E}$	$\hat{Y}$
1	.04%	−.54%	2.57%	−.54%	2.52%	.00%	5.97%	.30%	−3.42%	−.00%
2	.24%	−.54%	4.80%	−.54%	4.56%	.00%	4.68%	.30%	−5.85%	.00%
3	.62%	−.54%	5.18%	−.54%	4.56%	.00%	5.14%	.30%	−5.46%	.00%
4	−.34%	−.54%	2.18%	−.54%	2.52%	.00%	5.51%	.30%	−3.82%	.00%

Note.—Panel A shows the parameter values used in simulations 1 through 4. All other parameter values remain at their base case values (table 3). Panels B and C show simulation results for four endogenous variables ($\hat{r}$, $\hat{w}$, $\hat{E}_P$, and $\hat{E}_G$) in response to one of four exogenous policy changes. Panel D shows simulation results for total emissions ($\hat{E}$) and total output ($\hat{Y}$) in response to the same four policy changes, plus a change in the emissions tax ($\hat{\tau}$).

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places: a 10% increase in either subsidy increases the rental rate by 5.45% and decreases the wage rate by 2.32% (like the analytical results, these price changes are normalized relative to the price of the output good). The impacts on factor prices are driven by the factor share parameters. Since the subsidized sector is capital intensive, a subsidy (whether to capital or to output) benefits capital relatively more than it hurts labor. The pollution tax subsidy ($\hat{\phi}$) in panel C does not affect the rental rate or the wage to two decimal places. This is because pollution expenditure shares are so small that a change in that input price has minimal general equilibrium effects. The change in the labor constraint ($\widehat{\bar{L}}_G$) increases the capital price by 6.56% and decreases the labor price by 2.79%. This may seem counterintuitive, since an increase in the required use of labor seems like it should increase demand for labor and therefore its price. But, the overall labor resource constraint always binds, and thus the tightening of the labor constraint in the subsidized sector is equivalent to forcing labor out of the private sector. Because the private sector is labor intensive, an increase in the labor constraint decreases the demand for labor relative to the demand for capital, reducing the wage. These results are all consistent with equation (1). All of the coefficients on the right-hand side of equation (1) are increasing in the capital intensity of the subsidized sector (λ_{KG}), except the coefficient on $\hat{\tau}$.

5.2.2. *Base Case Pollution Results*

Next, consider the pollution effects of all four policy simulations under the base case parameter values. The capital subsidy ($\hat{\gamma}$) and output subsidy ($\hat{\varepsilon}$) both have identical effects (up to two decimal places) on pollution in the private sector (a 0.83% reduction), since the private sector's demand responds only to the input prices, which are identical under the two policy changes. By contrast, the 10% capital subsidy causes only a 0.33% increase in the subsidized sector's emissions, while the 10% output subsidy causes a 3.69% increase in the subsidized sector's emissions. The output subsidy substantially alters the quantity of output produced by the subsidized sector, not just its relative input prices. This increase in output of the subsidized sector is the primary driver of its increased emissions. The change in the pollution tax subsidy ($\hat{\phi}$) has no substantial effect (to two digits) on the private sector's emissions, but it increases the subsidized sector's emissions by 3.36%. Last, the change in the labor constraint ($\widehat{\bar{L}}_G$) decreases the private sector's emissions and increases the subsidized sector's emissions. The increase of 10% in the subsidized firm's labor requirement raises its emissions by just under 10%. This reflects the expression at the end of section 2 for the coefficient on $\widehat{\bar{L}}_G$ in the expression for $\hat{E}_G$. Although that expression could not be signed, most of its terms are positive, indicating a negative output effect (i.e., strengthening the labor constraint increases emissions). The labor constraint forces the subsidized firm to use more labor, producing more output. Tightening the labor constraint therefore increases output, which increases demand for the pollution input. The negative terms indicate the substitution effects from substituting emissions for labor. Since the overall sign is positive, the output effect dominates. These

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results are consistent with our solutions for emissions presented in equations (3) and (4) in section 3. For instance, comparing the effect of $\hat{\gamma}$ in equations (3) and (4) shows that the effect is smaller for $\hat{E}_P$ than for $\hat{E}_G$ (since B_G and B_P are both negative).

5.2.3. *Sensitivity Analysis*

Table 4 also considers alternate parameter values for the substitution elasticities in production as described above. Row 2 assumes that both sectors' elasticities are consistent with the estimates in Lu and Zhou (2009) in which labor is a better substitute for emissions than is capital (and in fact in which the cross-price elasticity between capital and emissions is zero). In rows 3 and 4, one sector's elasticity values are the base case values (capital the better substitute), while the other sector's elasticity values are the alternative values (labor the better substitute) The results of the simulations for each of these new parameter values are presented in the remaining rows of table 4.

Consider first how these different elasticity values affect the incidence results ($\hat{r}$ and $\hat{w}$). Differences between rows 1 through 4 for any of the four policy variables are smaller than two decimal places. The substitution elasticities in production that we vary do not substantively affect general equilibrium factor prices. From equation (1), the elasticities over capital and labor inputs affect the incidence results. Because those elasticities are known with more precision than the elasticities involving the pollution input, we do not vary them in the sensitivity analysis, which accounts for the invariance of the incidence results.

Next, we consider how the different elasticity values affect emissions ($\hat{E}_P$ and $\hat{E}_G$). For the capital subsidy $\hat{\gamma}$, the largest decrease in private sector emissions occurs in rows 2 and 4, where labor and emissions are strong substitutes in the private sector and capital and emissions are not substitutes. From equation (A4) and tables 3 and 4, in the base case, the decrease in private capital causes the private firm to substitute toward emissions, partially (but not completely) offsetting the decrease in emissions caused by substitution toward labor. The substitution of emissions for capital is not present in rows 2 and 4, and so the decrease in emissions is larger. The increase in subsidized sector emissions $\hat{E}_G$ is smallest in rows 1 and 4, where capital and emissions are better substitutes in the subsidized sector. This is because, although the market wage w has decreased in all rows, the shadow wage faced by the constrained firm, w_G, has actually risen, and so emissions from the constrained firm will increase more when its labor-emissions cross-price elasticity is higher. In all rows, the changes in the relative input prices (the same across all rows) have different effects on the demand for emissions based on each sector's substitution elasticity. Because changes in the substitution elasticities do not have large effects on the input prices, changes in the substitution elasticity in one sector do not materially affect emissions in the other sector.

For the output subsidy $\hat{\varepsilon}$, the emissions from the private sector mimics its emissions under the capital subsidy $\hat{\gamma}$ since the factor price affects the same. But the sub-

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sidized sector expands relative to the private sector under this policy, and so emissions increase by more in each row than they do under the capital subsidy $\hat{\gamma}$. When labor and emissions are strong substitutes in the subsidized sector (rows 2 and 3), the response of subsidized emissions to the output subsidy is larger. The price of emissions is fixed by policy, whereas the shadow price of labor increases, motivating the subsidized firm to substitute emissions for labor.

The emissions tax subsidy $\hat{\phi}$ has no effect on emissions in the private sector since it does not change any prices that sector faces. It changes the relative price of emissions for the subsidized sector, and thus the increased subsidy (lower net emissions price) increases the emissions of that sector. When the substitutability between emissions and labor is large in the subsidized sector (rows 2 and 3), the increase in its emissions is larger.

The tightening of the labor constraint ($\widehat{\bar{L}}_G = 10\%$) always decreases emissions in the private sector and increases emissions in the subsidized sector. This is due to an output effect (the private sector contracts and the subsidized sector expands). But the magnitude of the change in emissions depends on the substitution effects. When the private sector has more ability to substitute between emissions and labor (rows 2 and 4), the decrease in the wage causes more substitution of labor for emissions. When the subsidized sector has more ability to substitute between emissions and capital (rows 1 and 4), its emissions increase is larger.

5.2.4. *Total Emissions and Total Output*

Last, panel D of table 4 explores the effect of these policy changes on total emissions $\hat{E}$ and on total output $\hat{Y}$. In addition to the four policy changes from panels B and C, in panel D we present the change in total emissions and output in response to a 10% increase in τ, the emissions tax. This tax increase directly applies to both the subsidized and private sectors, in contrast to the four other policies. Equation (8) gives the analytical equation for total emissions.

First consider emissions. SOEs account for 75% of total sulfur emissions, so for cases in which private and SOE emissions move in opposite directions, the change in subsidized emissions receives more weight. Therefore, the capital subsidy ($\hat{\gamma}$) increases total emissions slightly, because the larger effect on private sector emissions receives less weight. Subsidizing the capital accumulation of pollution-intensive SOEs has a surprisingly small effect on total emissions due to general equilibrium effects: the resulting rise in the price of capital causes private firms to reduce output and therefore pollution.

In contrast, the output ($\hat{\varepsilon}$) and pollution ($\hat{\phi}$) subsidies have a much larger effect on SOE emissions, so the increase in total emissions is still substantial, despite the offsetting reduction in emissions from the private sector. Similarly, tightening the labor constraint ($\widehat{\bar{L}}_G$) has a larger effect on emissions from SOEs, so overall emissions rise despite the decrease in private sector emissions.

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An increase in the pollution tax ($\hat{\tau}$) directly decreases pollution in both sectors. Therefore, total emissions are usually more sensitive to the pollution tax than to other policies, which have offsetting effects on pollution across sectors. However, strengthening the labor constraint actually affects pollution more than increasing the pollution tax, since moving labor into the subsidized sector causes output and therefore pollution to rise substantially in that sector. Further, changes in the output and emissions subsidies affect total emissions by a similar order of magnitude as changes in the emissions tax.

Next consider output. SOEs account for just 37% of total output. Under any set of elasticity parameter values, both the capital and output subsidies decrease total output by about one-half of one percent. The increase in SOE output is dominated by the decrease in private sector output. Both the emissions tax and the emissions tax subsidy have a negligible (zero to two decimal places) effect on total output, because neither policy has a substantial effect on factor prices. Tightening the labor constraint has a slight positive effect on total output. It moves workers from the private sector into SOEs, and the increase in their productivity in SOEs (moving down along a diminishing marginal product curve) outweighs the decrease in average productivity in the private sector.

When output and pollution move in opposite directions, there is an opportunity for a preference-independent Pareto improvement. For all parameter values, a 10% increase in the output subsidy both lowers output and increases emissions; thus a decrease in the output subsidy creates a Pareto improvement. For most parameter values, including the base case, a decrease in the capital subsidy also provides a Pareto improvement. For the other three policies, any policy change results in a trade-off between emissions and output.

5.2.5. *Extensions*

We have conducted sensitivity analysis over the production substitution elasticities because those parameters are very uncertain. Under an even wider range of substitution elasticity values, the results are broadly consistent. In these simulations, reported in appendix table A2, we even allow for some of the cross-price elasticities to be negative, indicating complementary inputs (although note that these parameter values are arbitrarily chosen and not based on previous empirical estimates). When emissions and labor are very strong substitutes in the subsidized firm ($e_{G,EL} = 2$) then the response of emissions in the subsidized firm is substantially larger (e.g., a 10% increase in the output subsidy increase emissions by 19%). We also present simulation results of the two model extensions that are described in appendix A.IV; these simulations are reported in appendix A.IX.

6. CONCLUSION

We present an analytical general equilibrium model to study the effects of distortionary subsidies on incidence, pollution, and welfare. Policies intended to support

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one firm or one sector, like input or output price subsidies, have general equilibrium price effects that affect pollution and welfare. We calibrate the model to gauge the numerical magnitude of these effects and, in particular, to examine how they depend on the substitution elasticities in production. The incidence effects (factor prices) are relatively unaffected by substitution elasticities, but emissions are substantially affected by the substitution elasticities. The better substitute pollution is for an input whose price increases, the more emissions will increase. We find some parameter values for which a preference-independent Pareto improvement is possible—reducing emissions and increasing output.

Many studies in environmental economics examine the effect of environmental regulation, such as pollution taxes, on the environment. This paper argues that the unintended consequences of non-environmental policies on pollution are also important. Indeed, we show that reducing output and emissions subsidies to pollution-intensive firms can reduce pollution by about as much as raising emissions taxes. Policies that reduce employment at subsidized firms may have even larger effects on emissions than raising emissions taxes. Further, reducing non-environmental subsidies has welfare benefits associated with moving capital and labor to more productive sectors, in addition to reducing pollution. Therefore, reducing subsidies can be a rare win-win environmental policy: emissions fall without the usual loss of output. Reducing subsidies is always welfare increasing, regardless of preexisting policies, when the subsidized sector is of intermediate size. A calibration and simulation to China indicates that reducing capital subsidies is such a win-win policy.

Our model is simple and omits many features of an economy that might also affect emissions and incidence. However, its simplicity is a virtue in that it allows us to isolate individual effects without confounding complications. Our calibration is based on data from China, where our data source clearly delineates between subsidized and nonsubsidized firms. The model can be applied to other economies and other industries. Further work could consider, for example, how subsidies to domestic auto manufacturing firms affected prices and emissions from that sector in the United States, or how agricultural subsidies in OECD countries affect emissions.

APPENDIX

A.I. Details of the Model

Totally differentiating the equations that equate factor supply and demand, noting that both $\bar{K}$ and $\bar{L}$ are constant, yields

$$\hat{K}_P\lambda_{KP} + \hat{K}_G\lambda_{KG} = 0, \tag{A1}$$

$$\hat{L}_P\lambda_{LP} + \hat{L}_G\lambda_{LG} = 0. \tag{A2}$$

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We follow Mieszkowski (1972) in modeling the private firm's choices over its inputs. Totally differentiating the private firm's three input demand equations yields two independent equations:[35]

$$\hat{K}_P - \hat{L}_P = (e_{P,KK} - e_{P,KL})\theta_{PK}\hat{r} + (e_{P,KE} - e_{P,EL})\theta_{PE}\hat{\tau} + (e_{P,KL} - e_{P,LL})\theta_{PL}\hat{w}, \tag{A3}$$

$$\hat{E}_P - \hat{L}_P = (e_{P,KE} - e_{P,KL})\theta_{PK}\hat{r} + (e_{P,EE} - e_{P,EL})\theta_{PE}\hat{\tau} + (e_{P,EL} - e_{P,LL})\theta_{PL}\hat{w}. \tag{A4}$$

The parameters $e_{P,ij}$ are the Allen elasticities of substitution (Allen 1938).

Totally differentiating the private firm's zero-profit condition yields

$$\hat{q}_P + \hat{P} = \theta_{PK}\left(\hat{r} + \hat{K}_P\right) + \theta_{PL}\left(\hat{w} + \hat{L}_P\right) + \theta_{PE}\left(\hat{\tau} + \hat{E}_P\right). \tag{A5}$$

Totally differentiating the private firm's production function and substituting in the first-order conditions from the firm's profit maximization problem (marginal revenue product equals marginal cost, for each input) gives

$$\hat{P} = \theta_{PK}\hat{K}_P + \theta_{PL}\hat{L}_P + \theta_{PE}\hat{E}_P. \tag{A6}$$

The subsidized firm's cost-minimization problem is analogous to the private firm's cost-minimization problem, except the subsidized firm faces different input costs (e.g., replacing r with r_G, the subsidized capital price) and the binding constraint on labor input, $\bar{L}_G$. Because of this constraint, the subsidized firm no longer is able to set its marginal revenue product of labor equal to the wage. Rather, the constraint creates a shadow price of labor for the subsidized firm, denoted w_G. This shadow price equals the difference between the market wage w and the multiplier on the labor constraint. Since we always assume that the labor constraint is binding, the market price w is strictly greater than the shadow price w_G.

The solution to the firm's cost-minimization problem can thus be written in terms of the shadow price of the constraint and the other subsidized prices in a manner similar to equations (3) and (4).[36]

$$\hat{K}_G - \hat{L}_G = (e_{G,KK} - e_{G,KL})\theta_{GK}\hat{r}_G + (e_{G,KE} - e_{G,EL})\theta_{GE}\hat{\tau}_G + (e_{G,KL} - e_{G,LL})\theta_{G\bar{L}}\hat{w}_G \tag{A7}$$

$$\hat{E}_G - \hat{L}_G = (e_{G,KE} - e_{G,KL})\theta_{GK}\hat{r}_G + (e_{G,EE} - e_{G,EL})\theta_{GE}\hat{\tau}_G + (e_{G,EL} - e_{G,LL})\theta_{G\bar{L}}\hat{w}_G. \tag{A8}$$

---

35. The analytical general equilibrium modeling and solution strategy that we employ is in the style of Harberger (1962). Other papers using similar methods include Mieszkowski (1972), Fullerton and Metcalf (2002), Fullerton and Heutel (2007), and Fullerton and Heutel (2010). See, e.g., Fullerton and Heutel (2007, 588–89) for a derivation of equations (A3)–(A4).

36. An alternate method of modeling the binding labor constraint does not use the shadow price of labor and, instead, derives equations similar to (A7) and (A8) but that are in terms of the value of the labor constraint itself rather than the shadow price. This is similar to the method in Fullerton and Heutel (2010). This solution method is available upon request from the authors; and results in an identical solution to the one presented here.

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In equations (A7) and (A8), the parameters θ_{GK} and θ_{GE} are the share of total subsidized firm revenues paid to capital and pollution, respectively, less government subsidies (e.g., $\theta_{GK} \equiv r_G K_G / q_{GN} G$). However, the parameter $\theta_{G\bar{L}}$ is not equal to $wL_G / q_{GN} G$. Rather, $\theta_{G\bar{L}} \equiv w_G L_G / q_{GN} G$. In equations (A7) and (A8), demand for labor is a function of prices. Although the constraint implies $L_G = \bar{L}_G$, the constraint creates the shadow price w_G so that labor demand under that shadow price, according to equations (A7) and (A8), is just equal to the minimum labor. That is, the subsidized firm faces a shadow price of labor lower than the wage, which encourages the subsidized firm to use more labor than it otherwise would have used.

We first model the case where equilibrium profits, net of subsidies, must equal zero. Such an equilibrium condition might arise under free entry, for example.[37] In this case, one of the subsidy values is determined in equilibrium; we assume that the zero-profit condition determines S once the regulator chooses all of the other subsidies. Substituting the firm's first-order conditions from the cost-minimization problem into the zero-profit condition implies:

$$\pi_G = q_{GN} G - q_{GN} G_K K_G - q_{GN} G_E E_G - wL_G + S = 0,$$

where G_K and G_E are the derivatives of the production function with respect to inputs capital and pollution. Then, since production is constant returns to scale, using Euler's theorem for homogeneous functions yields

$$\pi_G = w_G L_G - wL_G + S = 0.$$

Thus equilibrium subsidies are $S = (w - w_G)L_G > 0$, since the minimum labor constraint binds. Substituting equilibrium direct subsidies into the zero profit condition and totally differentiating yields

$$\hat{q}_{GN} + \hat{G} = \theta_{GK}\left(\hat{r}_G + \hat{K}_G\right) + \theta_{G\bar{L}}\left(\hat{w}_G + \hat{L}_G\right) + \theta_{GE}\left(\hat{\tau}_G + \hat{E}_G\right). \tag{A9}$$

Similarly, totally differentiating the production function and substituting in the first-order conditions from the profit-maximization problem yields

$$\hat{G} = \theta_{GK}\hat{K}_G + \theta_{G\bar{L}}\hat{L}_G + \theta_{GE}\hat{E}_G. \tag{A10}$$

The direct subsidy S drops out of equations (A7)–(A10). One could solve for the change in the direct subsidy by totally differentiating $S = (w - w_G)L_G$, but it is not necessary to include to solve the system (that would add one equation and one variable that does not show up in any other equation). Intuitively, the lump-sum subsidy does

37. Alternatively, if one interprets S as a "bailout," the government may be motivated only to prevent bankruptcy, not to give positive profits to the subsidized firm.

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not affect the firm's decisions and therefore has no effect on any general equilibrium outcomes.[38]

It follows that the equations describing the subsidized firm's decisions, equations (A7) through (A10), are independent of the assumption that the firm earns zero profits. Indeed, we could assume instead that the firm's profits π_G are allowed to be positive, and that the level of firm profits is an exogenous policy parameter that can be controlled by the government. That is, the profits π_G represent rents that the regulator allows the firm to capture, perhaps through barriers to entry.

To see this, assume that $\pi_G > 0$. Then the equation relating firm profits to the shadow price of the constraint still holds, but firm profits no longer must equal zero:

$$\pi_G = w_G L_G - wL_G + S.$$

The endogenous direct subsidy S is now larger, given the positive exogenous level of profit π_G. Totally differentiating this equation yields

$$\hat{\pi}_G = \beta_{w_G}\left(\hat{w}_G + \hat{L}_G\right) - \beta_w\left(\hat{w} + \hat{L}_G\right) + \beta_S\hat{S},$$

where $\beta_{w_G} \equiv (w_G L_G)/\pi_G$, $\beta_w \equiv (wL_G)/\pi_G$, and $\beta_S \equiv S/\pi_G$. Similarly, totally differentiating the definition of the firm's profits yields

$$\hat{\pi}_G = \beta_{p_G}\left(\hat{q}_{GN} + \hat{G}\right) - \beta_r\left(\hat{r}_G + \hat{K}_G\right) - \beta_\tau\left(\hat{\tau}_G + \hat{E}_G\right) - \beta_w\left(\hat{w} + \hat{L}_G\right) + \beta_S\hat{S},$$

where $\beta_{p_G} \equiv (Gq_{GN})/\pi_G$, $\beta_\tau \equiv (\tau_G E_G)/\pi_G$, and $\beta_r \equiv (r_G K_G)/\pi_G$. Combining the above two equations, canceling terms, and multiplying everything by $\pi_G/q_{GN}G$ yields equation (A9). The derivation of equation (A10) does not depend on the assumption of zero profits. Thus, equations (A7) through (A10) hold as long as the direct subsidy is large enough so that subsidized profits are nonnegative. We are interested in the case where both firms choose to operate, where neither firm is at a corner solution for any of its input demands, and where our differential analysis is applicable. The condition $S \geq (w - w_G)L_G$ ensures the subsidized firm operates, and the private firm operates if and only if the cost of receiving subsidies is positive, which occurs when the minimum labor constraint binds, $w - w_G > 0$.[39]

The minimum labor constraint binds, which implies:

$$\hat{\bar{L}}_G = \hat{L}_G. \tag{A11}$$

38. The subsidized firm can only increase direct subsidies by increasing losses, so the direct subsidy is lump sum in the sense that profits net of subsidies are unchanged regardless of the subsidized firm's decisions.

39. In the case of Cobb-Douglas production functions, we can write the condition $w - w_G > 0$ in terms of the parameters. In the more general formulation here where we impose no functional forms, we cannot specify $w - w_G > 0$ in terms of the parameters. However, since in practice one can check $w - w_G > 0$ directly, this is not a great concern.

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Thus equations (A7)–(A11) characterize the subsidized firm's decisions. An alternative method to incorporating the binding labor constraint would be to set the input demand equation for labor equal to the labor constraint, then totally differentiate:

$$\hat{\bar{L}}_G = e_{G,KL}\theta_{GK}\hat{r}_G + e_{G,EL}\theta_{GE}\hat{\tau}_G + e_{G,LL}\theta_{G\bar{L}}\hat{w}_G + \hat{G}. \tag{A11$'$}$$

Equation (A11′) demonstrates that the input demand equation, in terms of the Allen elasticities and the input prices, characterizes the subsidized firm's demand for labor, which must equal the required minimum labor. It can be shown that equation (A11′) can be derived from equations (A7), (A8), and (A11) given known restrictions on the Allen elasticities. Thus, replacing equation (A11) with (A11′) yields identical solutions.

The two firms produce identical goods, so perfect competition implies that consumer prices are equal:

$$\hat{q}_P = \hat{q}_G. \tag{A12}$$

The consumer price for the subsidized firm's output is not equal to the price net of subsidies that the firm faces, q_{GN}.

Finally, government policy determines the relative prices faced by the subsidized firm. Totally differentiating the definition $r_G \equiv r(1-\gamma)$ yields

$$\hat{r}_G = \hat{r} - \hat{\gamma}, \tag{A13}$$

where $\hat{r}_G$ and $\hat{r}$ again are proportional changes (e.g., $\hat{r} = dr/r$), but $\hat{\gamma} \equiv d\gamma/(1-\gamma)$. Similarly,

$$\hat{\tau}_G = \hat{\tau} - \hat{\phi} \tag{A14}$$

$$\hat{q}_{GN} = \hat{q}_G + \hat{\varepsilon}, \tag{A15}$$

where $\hat{\phi} \equiv d\phi/(1-\phi)$ and $\hat{\varepsilon} = d\varepsilon/(1+\varepsilon)$.

A.II. Proof of Proposition 1

Existence of Equilibrium

We first show that, under the conditions of the proposition, a unique equilibrium exists such that the private firm has positive output. The solution is then interior, which allows for the marginal analysis in the rest of the proof. An equilibrium requires that the first-order conditions of both firms are satisfied, supply equals demand in the input markets, and the Kuhn-Tucker condition holds for the labor constraint. Consider first the firm first-order conditions for all inputs except labor. Under constant returns to scale, marginal products are homogeneous of degree zero. Therefore, firm input demands are:

$$r = f_K(k_P, e_P),$$

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$$r_G = (1+\varepsilon)A_G f_K(k_G, e_G),$$

$$\tau = f_E(k_P, e_P),$$

$$\tau_G = (1+\varepsilon)A_G\, f_E(k_G, e_G).$$

Here $k_G \equiv K_G/L_G$ and analogously for e_G, k_P, and e_P and $f_K(k_G, e_G) \equiv F_K(k_G, 1, e_G)$ and analogously for f_E. Next we solve the last two equations implicitly to get:

$$e_P = e(k_P, \tau),$$

$$e_G = e(k_G, \xi\tau),\ \xi \equiv \frac{1-\phi}{(1+\varepsilon)A_G}.$$

Hence an equilibrium in the input markets occurs if the constraint binds and:

$$G(k_G) \equiv f_K(k_G, e(k_G, \xi\tau)) - \rho f_K(k_P(k_G), e(k_P(k_G), \tau)) = 0,$$

$$\rho \equiv \frac{1-\gamma}{(1+\varepsilon)A_G},\ k_P(k_G) = \frac{\bar{k} - \lambda_{LG}k_G}{\lambda_{LP}}.$$

Here the last equation is the per capita version of the equilibrium condition for the capital market. Finally, $\xi, \rho > 1$ since by assumption $A_G(1+\varepsilon) < \min(1-\gamma, 1-\phi)$.

Next, note that $f_K(k_G, e(k_G, \xi\tau))$ is decreasing in k_G since $f_{KK} f_{EE} - (f_{KE})^2 > 0$ by concavity of F. Therefore, G is decreasing in k_G. Given $f_{KE} > 0$, $f_K(k, e(k, \tau))$ is decreasing in τ. Next, $k_P(\bar{k}) = \bar{k}$ and since by assumption $\xi, \rho > 1$:

$$f_K(\bar{k}, e(\bar{k}, \xi\tau)) < f_K(\bar{k}, e(\bar{k}, \tau)) < \rho f_K(\bar{k}, e(\bar{k}, \tau)).$$

The above inequalities imply $G(\bar{k}) < 0$. Further, G is continuous and $G(0) = \infty$ by the Inada conditions. Therefore, there exists a unique $k_G^* \in (0, \bar{k})$ which satisfies $G(k_G^*) = 0$. In essence, the assumptions imply that the TFP in the subsidized sector is sufficiently low so as to more than offset the subsidies, making capital less productive in the subsidized sector. Therefore, the subsidized sector must have a lower capital to labor ratio than the private sector, with the economy-wide capital to labor ratio $\bar{k}$ being in the middle.

Equilibrium also requires that the Kuhn-Tucker condition holds for k_G^*. From the subsidized firm's problem, $w_G \leq w$. That is, either labor is strictly less productive in the subsidized sector and the constraint binds or the constraint does not bind and the marginal product of labor is equal across sectors. Substituting the marginal products implies:

$$F_L(k_G, 1, e(k_G, \xi\tau)) \leq \frac{1}{(1+\varepsilon)A_G} F_L(k_P(k_G), 1, e(k_P(k_G), \tau)).$$

$$H \equiv \frac{1}{(1+\varepsilon)A_G} h(k_P(k_G), e(k_P(k_G), \tau)) - h(k_G, e(k_G, \xi\tau)) \geq 0,\ h \equiv f - kf_K - ef_E.$$

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Next, H is decreasing in k_G by concavity and decreasing in τ for $f_{EL} > 0$. Therefore:

$$h\left(\bar{k}, e\left(\bar{k}, \xi\tau\right)\right) < h\left(\bar{k}, e\left(\bar{k}, \tau\right)\right) < \frac{1}{(1+\varepsilon)A_G} h\left(\bar{k}, e\left(\bar{k}, \tau\right)\right).$$

Therefore, $H(\bar{k}) > 0$ and the constraint binds at $\bar{k}$. Since H is decreasing, the constraint also binds for any $k_G < \bar{k}$. Since $k_G^* < \bar{k}$, the constraint binds and an equilibrium exists.[40]

Derivation of Equation (1)

We next derive equation (1) from equations (A1)–(A15). Given the price normalization, $\hat{q}_P = \hat{q}_G = 0$. After eliminating the output prices, a linear system of 14 equations and 14 unknowns remain. First we eliminate $\hat{\tau}_G$, $\hat{r}_G$, and $\hat{q}_{GN}$ using (A13)–(A15), $\hat{P}$, $\hat{G}$, and $\hat{L}_G$, using equations (A6), (A10), and (A11), and $\hat{K}_P$ and $\hat{L}_P$ using (A1) and (A2). The remaining system of six equations are:

$$-\hat{K}_G\frac{\lambda_{KG}}{\lambda_{KP}} + \hat{\bar{L}}_G\frac{\lambda_{LG}}{\lambda_{LP}} = (e_{P,KK} - e_{P,KL})\theta_{PK}\hat{r} + (e_{P,KE} - e_{P,EL})\theta_{PE}\hat{\tau} + (e_{P,KL} - e_{P,LL})\theta_{PL}\hat{w}, \tag{A1$'$}$$

$$\hat{E}_P + \hat{\bar{L}}_G\frac{\lambda_{LG}}{\lambda_{LP}} = (e_{P,KE} - e_{P,KL})\theta_{PK}\hat{r} + (e_{P,EE} - e_{P,EL})\theta_{PE}\hat{\tau} + (e_{P,EL} - e_{P,LL})\theta_{PL}\hat{w}. \tag{A2$'$}$$

$$0 = \theta_{PK}\hat{r} + \theta_{PL}\hat{w} + \theta_{PE}\hat{\tau}. \tag{A3$'$}$$

$$\hat{K}_G - \hat{\bar{L}}_G = (e_{G,KK} - e_{G,KL})\theta_{GK}(\hat{r} - \hat{\gamma}) + (e_{G,KE} - e_{G,EL})\theta_{GE}\left(\hat{\tau} - \hat{\phi}\right) + (e_{G,KL} - e_{G,LL})\theta_{G\bar{L}}\hat{w}_G \tag{A4$'$}$$

$$\hat{E}_G - \hat{\bar{L}}_G = (e_{G,KE} - e_{G,KL})\theta_{GK}(\hat{r} - \hat{\gamma}) + (e_{G,EE} - e_{G,EL})\theta_{GE}\left(\hat{\tau} - \hat{\phi}\right) + (e_{G,EL} - e_{G,LL})\theta_{G\bar{L}}\hat{w}_G \tag{A5$'$}$$

$$\hat{\varepsilon} = \theta_{GK}(\hat{r} - \hat{\gamma}) + \theta_{G\bar{L}}\hat{w}_G + \theta_{GE}\left(\hat{\tau} - \hat{\phi}\right). \tag{A6$'$}$$

Equations (A1′), (A3′), (A4′), and (A6′) form a subset of equations that solve for $\hat{r}$, $\hat{K}_G$, $\hat{w}$, and $\hat{w}_G$. Solving (A6′) for $\hat{w}_G$ and then (A4′) for $\hat{K}_G$ yields a system of two equations:

40. Reversing the arguments, if $A_G(1+\varepsilon) > \max(1-\gamma, 1-\phi)$, then the subsidized firm has the greater capital to labor ratio, but $H(\bar{k}) < 0$, so the constraint does not bind for any $k_G^* > \bar{k}$. So the constraint does not bind at k_G^*. In the unconstrained case, equilibrium requires $w_G = w$ or $H(k_G^*) = 0$. However, $H(k_G^*) < 0$, so no equilibrium exists in this case.

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$$\hat{\hat{L}}_G\left(\frac{\lambda_{LG}}{\lambda_{LP}}-\frac{\lambda_{KG}}{\lambda_{KP}}\right)=(e_{P,KK}-e_{P,KL})\theta_{PK}\hat{r}+\frac{\lambda_{KG}}{\lambda_{KP}}(e_{G,EL}-e_{G,LL})\hat{\varepsilon}$$
$$+\frac{\lambda_{KG}}{\lambda_{KP}}(e_{G,KK}-2e_{G,KL}+e_{G,LL})\theta_{GK}(\hat{r}-\hat{\gamma})+(e_{P,KE}-e_{P,EL})\theta_{PE}\hat{\tau}$$
$$+\frac{\lambda_{KG}}{\lambda_{KP}}(e_{G,KE}-e_{G,EL}-e_{G,KL}+e_{GLL})\theta_{GE}\left(\hat{\tau}-\hat{\phi}\right)+(e_{P,KL}-e_{P,LL})\theta_{PL}\hat{w}, \tag{A1$''$}$$

$$0=\theta_{PK}\hat{r}+\theta_{PL}\hat{w}+\theta_{PE}\hat{\tau}. \tag{A2$''$}$$

Using (A2″) to eliminate $\hat{w}$ yields equation (1).

Proof That $D > 0$

If $e_{i,KK}-2e_{i,KL}+e_{i,LL}$ is negative regardless of $i = G, L$, then $D > 0$. Dropping the subscript i for convenience and using the definition of Allen elasticity, we have:

$$e_{KK}-2e_{KL}+e_{LL}=\frac{|B_{KK}|}{|B|K^2}-2\frac{|B_{KL}|}{|B|KL}+\frac{|B_{LL}|}{|B|L^2}=\frac{1}{|B|K^2L^2}(L^2|B_{KK}|-2|B_{KL}|KL+K^2|B_{LL}|).$$

Here B is the bordered Hessian from the firm's cost-minimization problem, and B_{ij} is the bordered Hessian with column i being all zeros except a one at row j. Since the determinant of the bordered Hessian is negative by concavity, we must show the last term is positive. Evaluating the determinants in the last term results in:

$$L^2|B_{KK}|-2|B_{KL}|KL+K^2|B_{LL}|=2L^2f_Lf_E-L^2f_L^2f_{EE}$$
$$-L^2f_E^2f_{LL}+2KLf_Ef_Kf_{EL}-2KLf_E^2f_{KL}-2KLf_Kf_Lf_{EE}$$
$$+2KLf_Ef_Lf_{KE}+2K^2f_Ef_Kf_{KE}-K^2f_K^2f_{EE}-K^2f_E^2f_{KK}.$$

Since f is constant returns to scale, the marginal products are homogeneous degree zero. Therefore:

$$f_{KK}=-\frac{Lf_{KL}+Kf_{KE}}{K}, \tag{A16}$$

$$f_{LL}=-\frac{Kf_{KL}+Ef_{EL}}{L}, \tag{A17}$$

$$Lf_{EL}+Kf_{KE}=-Ef_{EE}. \tag{A18}$$

Substituting in equations (A16)–(A17), collecting terms, and then substituting in (A18) results in:

$$L^2|B_{KK}|-2|B_{KL}|KL+K^2|B_{LL}|=-f_{EE}(Lf_L+Kf_K+Ef_E)^2=-f_{EE}Y^2>0.$$

Here the last equality follows from Euler's theorem and the term is positive by concavity. Hence, we have:

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$$e_{i,KK} - 2e_{i,KL} + e_{i,LL} = \frac{-f_{i,EE}Y_i^2}{|B_i|K_i^2 L_i^2} > 0. \tag{A19}$$

The sign of the above equation is independent of i and is negative by concavity which completes the proof.

Comparative Statics

That $\partial\hat{r}/\partial\hat{\gamma} > 0$ follows from the proof that $D > 0$. Next, $D > 0$ implies $\partial\hat{r}/\partial\hat{\phi} > 0$ if and only if $B_G < 0$, which we show in appendix A.III holds if and only if $f_{KE} < 0$. The condition for $\partial\hat{r}/\partial\hat{\tau}$, follows using identical reasoning as $\hat{\phi}$. From equation (1), $\partial\hat{r}/\partial\hat{\varepsilon} > 0$ since $D > 0$, all own-price Allen elasticities are negative, and we have assumed all cross-price Allen elasticities are positive ($e_{G,KL} > 0$ in $\partial\hat{r}/\partial\hat{\varepsilon}$). The condition for $\partial\hat{r}/\partial\hat{\bar{L}}_G > 0$ follows directly from $D > 0$ and equation (1).

A.III. Condition for $B_G > 0$

We have:

$$B_G \equiv e_{G,KE} - e_{G,EL} - e_{G,KL} + e_{G,LL}, = \frac{1}{|B|KEL^2}(L^2|B_{KE}| - KL|B_{EL}| - EL|B_{KL}| + KE|B_{LL}|).$$

Evaluating the determinants, substituting in (A1)–(A2), and the (A3) yields:

$$B_G = \frac{1}{|B|KEL^2}\left(-f_{KE}(Lf_L + Kf_K + Ef_E)^2\right) = \frac{-f_{KE}Y^2}{|B|KEL^2}.$$

Since the determinant of B is negative by concavity, the above equation is positive if and only if an increase in emissions raises the marginal product of capital ($f_{KE} > 0$).

A.IV. Extensions to the Model

Allowing for the two output goods to be distinct (imperfect substitutes) creates a series of new incidence effects, but the effects that we have identified so far remain. Dropping the labor constraint but keeping the assumption of identical output goods results in an equilibrium where only one firm exists.[41] So, in the extension that drops the labor constraint, we also allow for the two output goods to be imperfect substitutes. To allow for imperfect substitutes, we replace equation (A12) with the following equation:

$$\hat{G} - \hat{P} = \sigma_u(\hat{q}_P - \hat{q}_G).$$

The constant σ_u represents the elasticity of substitution in consumption between the two output goods. It is defined to be positive, with a higher value indicating higher

41. Which firm dominates depends on the size of the subsidies.

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substitutability. The limit where $\sigma_u \to \infty$ represents the case of perfect substitutes, as in the base model. All of the other equations are identical.

Under the first extension (imperfect substitutes and a labor constraint), the closed-form solution for the change in the capital price is:

$$
\hat{r} = \frac{1}{D'} \left\{ \begin{array}{c}
\left[\begin{array}{c} -\theta_{GK}\lambda_{KG}(e_{G,KK} - 2e_{G,KL} + e_{G,LL}) + \\ \frac{1}{\sigma_u}\lambda_{KG}\left[(e_{G,KL} - e_{G,LL})S_{r_G} - \frac{\theta_{GK}}{\theta_{G\bar{L}}}(e_{G,KK} - e_{G,KL})S_{w_G}\right] \end{array} \right] \hat{\gamma} \\
+ \lambda_{KG}(e_{G,KL} - e_{G,LL})\hat{\varepsilon} + \\
\left[-\theta_{GE}\lambda_{KG}B_G + \frac{1}{\sigma_u}\left[\lambda_{KG}(e_{G,KL} - e_{G,LL})S_{\tau_G} - \lambda_{KG}\frac{\theta_{GE}}{\theta_{G\bar{L}}}(e_{G,KE} - e_{G,EL})S_{w_G}\right]\right]\hat{\phi} \\
+ \left[\lambda_{KP}\left(\frac{\lambda_{KG}}{\lambda_{KP}} - \frac{\lambda_{LG}}{\lambda_{LP}}\right) + \frac{1}{\sigma_u}\ \frac{\lambda_{KP}}{\theta_{G\bar{L}}}\left[S_{w_G}\left(\frac{\lambda_{KG}}{\lambda_{KP}} - \frac{\lambda_{LG}}{\lambda_{LP}}\right) + MS_{L_G}\right]\right]\widehat{\bar{L}}_G \\
+ \left[\begin{array}{c} (\theta_{GE}\lambda_{KG}B_G + \theta_{PE}\lambda_{KP}B_P) + \\ \frac{1}{\sigma_u}\left[\begin{array}{c} \lambda_{KP}\frac{\theta_{PE}}{\theta_{G\bar{L}}}S_{w_G}B_P + M\frac{\lambda_{KP}}{\theta_{G\bar{L}}}S_{\tau_P} - \lambda_{KG}(e_{G,KL} - e_{G,LL})S_{\tau_G} + \\ \lambda_{KG}\frac{\theta_{GE}}{\theta_{G\bar{L}}}(e_{G,KE} - e_{G,EL})S_{w_G} - \lambda_{KP}\frac{\theta_{PE}}{\theta_{G\bar{L}}}(e_{P,KL} - e_{P,LL})S_{w_G} - \\ \lambda_{KP}\frac{\theta_{PE}}{\theta_{PL}}\ \frac{M}{\theta_{G\bar{L}}}S_{w_P} \end{array} \right] \end{array} \right]\hat{\tau}
\end{array} \right\}
$$

Here B_P and B_G are defined as in the main text, and the other constants are defined as follows:

$$
\begin{aligned}
D' \equiv \Bigg\{ & -\lambda_{KG}\theta_{GK}(e_{G,KK} - 2e_{G,KL} + e_{G,LL}) - \lambda_{KP}\theta_{PK}(e_{P,KK} - 2e_{P,KL} + e_{P,LL}) + \frac{1}{\sigma_u}\frac{\lambda_{KP}}{\theta_{G\bar{L}}} \\
& \left[S_{w_G}\theta_{PK}(-e_{P,KK} + 2e_{P,KL} - e_{P,LL}) + MZ\theta_{PE}\theta_{PK}B_P + MS_{r_G} - S_{w_G}\frac{\lambda_{KG}}{\lambda_{KP}}\theta_{GK}(e_{G,KK} - e_{G,KL})\right]\Bigg\} \\
\equiv {} & D + \frac{1}{\sigma_u}D_S.
\end{aligned}
$$

$$
M \equiv \frac{\lambda_{KG}}{\lambda_{KP}}(e_{G,KL} - e_{G,LL})\theta_{G\bar{L}}
$$

$$
Z \equiv \left(\theta_{PK}\frac{\lambda_{KG}}{\lambda_{KP}} + \theta_{GK}\right)
$$

$$
S_{r_G} \equiv \theta_{GE}\theta_{GK}(e_{G,KE} - e_{G,KL}) + Z\theta_{GK}(e_{G,KK} - e_{G,KL})
$$

$$
S_{w_G} \equiv \theta_{GE}\theta_{G\bar{L}}(e_{G,EL} - e_{G,LL}) + Z\theta_{G\bar{L}}(e_{G,KL} - e_{G,LL})
$$

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$$S_{\tau_G} \equiv (\theta_{GE})^2(e_{G,EE} - e_{G,EL}) + Z\theta_{GE}(e_{G,KE} - e_{G,EL})$$

$$S_{L_G} \equiv -Z + \frac{\lambda_{LG}}{\lambda_{LP}}(-\theta_{PE} - \theta_{PL}) - \theta_{G\bar{L}} - \theta_{GE}$$

$$S_{r_P} \equiv \theta_{PE}\theta_{PK}(e_{P,KE} - e_{P,KL})$$

$$S_{\tau_P} \equiv (\theta_{PE})^2(e_{P,EE} - e_{P,EL})$$

$$S_{w_P} \equiv \theta_{PE}\theta_{PL}(e_{P,EL} - e_{P,LL})$$

As the two output goods become perfect substitutes (i.e., as $\sigma_u \to \infty$ or $1/\sigma_u \to 0$), this complex equation becomes equation (1), the equation for $\hat{r}$ with the assumption of perfect substitutes. That is, all of the effects that are present in equation (1) and that we discuss earlier are still present in this more complicated model. In addition, there are other effects that arise from the imperfect substitutability of the two goods; these are the parts of the above equation that are multiplied by $1/\sigma_u$. These effects depend on factor shares and on factor demand elasticities, and all of these effects are proportional to $1/\sigma_u$. It is difficult to sign these additional effects without further assumptions. Instead, later in the appendix, we will determine the magnitude of these additional effects in a calibrated version of the model. However, the coefficient on $\hat{\varepsilon}$ in the above equation is identical to the corresponding coefficient in equation (1); the substitutability of the output goods has no effect on the relationship between the output subsidy ε and the factor prices.

We next consider an extension in which the labor constraint is not included and the goods are imperfect substitutes. All of the equations are identical to those in the base case, except that equation (A11) is dropped (the labor constraint) and equation (A12) becomes: $\hat{G} - \hat{P} = \sigma_u(\hat{q}_P - \hat{q}_G)$. Furthermore, an additional equation arises, $\hat{w}_G = \hat{w}$, since removing the constraint removes the wedge between the marginal product of labor in the two sectors. The solution for the capital price change is

$$\hat{r} = \frac{1}{D''}\Bigg\{\left[-\theta_{GK}\theta_{PL} - \frac{1}{\sigma_u}\frac{1}{N}\theta_{PL}Y_{r\gamma}\right]\hat{\gamma} - \theta_{PL}\hat{\varepsilon} + \left[-\theta_{GE}\theta_{PL} + \frac{1}{\sigma_u}\frac{1}{N}\theta_{PL}Y_{\tau\phi}\right]\hat{\phi} + \left[(\theta_{GE}\theta_{PL} - \theta_{GL}\theta_{PE}) + \frac{1}{\sigma_u}\frac{1}{N}(-Y_w - \theta_{PL}Y_{\tau\phi} - \theta_{PL}Y_\tau)\right]\hat{\tau}\Bigg\}.$$

Here $D'' \equiv (\theta_{GL}\theta_{PK} - \theta_{GK}\theta_{PL}) + (1/\sigma_u)(1/N)(-\theta_{PL}Y_r - \theta_{PL}Y_{r\gamma} + \theta_{PK}Y_w)$, and N and the Y constants are defined as follows:

$$N \equiv \left(\frac{\lambda_{LG}}{\lambda_{LP}} - \frac{\lambda_{KG}}{\lambda_{KP}}\right)$$

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$$Y_r \equiv \theta_{PK}\left\{-N\theta_{PE}(e_{P,KE}-e_{P,KL}) + \left(\theta_{PK}\frac{\lambda_{KG}}{\lambda_{KP}} + (\theta_{PL}+\theta_{PE})\frac{\lambda_{LG}}{\lambda_{LP}} + 1\right)(e_{P,KK}-e_{P,KL})\right\}$$

$$\begin{aligned} Y_{r\gamma} \equiv \theta_{GK}\Bigg\{ & N\theta_{GE}(e_{G,KE}-e_{G,KL}) \\ & + \left[\frac{\lambda_{KG}}{\lambda_{KP}}\left(\theta_{PK}\frac{\lambda_{KG}}{\lambda_{KP}} + \theta_{GK}\right) + \frac{\lambda_{KG}}{\lambda_{KP}}\left(\frac{\lambda_{LG}}{\lambda_{LP}}(\theta_{PL}+\theta_{PE}) + \theta_{GL} + \theta_{GE}\right)\right](e_{G,KK}-e_{G,KL})\Bigg\} \end{aligned}$$

$$\begin{aligned} Y_w \equiv & [N(-\theta_{PE}\theta_{PL}(e_{P,EL}-e_{P,LL}) + \theta_{GE}\theta_{GL}(e_{G,EL}-e_{G,LL}))] \\ & + \left[\left(\theta_{PK}\frac{\lambda_{KG}}{\lambda_{KP}} + \theta_{GK}\right)\left(\theta_{GL}\frac{\lambda_{LG}}{\lambda_{LP}}(e_{G,KL}-e_{G,LL}) + \theta_{PL}(e_{P,KL}-e_{P,LL})\right)\right] \\ & + \left[\left(\frac{\lambda_{LG}}{\lambda_{LP}}(\theta_{PL}+\theta_{PE}) + \theta_{GL} + \theta_{GE}\right)\left(\theta_{PL}(e_{P,KL}-e_{P,LL}) + \frac{\lambda_{KG}}{\lambda_{KP}}\theta_{GL}(e_{G,KL}-e_{G,LL})\right)\right] \end{aligned}$$

$$\begin{aligned} Y_\tau \equiv & \left[N\theta_{PE}^2(e_{P,EE}-e_{P,EL})\right] + \left[\left(-\theta_{PK}\frac{\lambda_{KG}}{\lambda_{KP}} - \theta_{GK}\right)\theta_{PE}(e_{P,KE}-e_{P,EL})\right] \\ & + \left[\left(\frac{\lambda_{LG}}{\lambda_{LP}}(-\theta_{PL}-\theta_{PE}) - \theta_{GL} - \theta_{GE}\right)\theta_{PE}(e_{P,KE}-e_{P,EL})\right] \end{aligned}$$

$$\begin{aligned} Y_{\tau\phi} \equiv & \left[-N\theta_{GE}^2(e_{G,EE}-{}_{G,EL})\right] + \left[\left(-\theta_{PK}\frac{\lambda_{KG}}{\lambda_{KP}} - \theta_{GK}\right)\theta_{GE}\frac{\lambda_{LG}}{\lambda_{LP}}(e_{G,KE}-e_{G,EL})\right] \\ & + \left[\left(\frac{\lambda_{LG}}{\lambda_{LP}}(-\theta_{PL}-\theta_{PE}) - \theta_{GL} - \theta_{GE}\right)\frac{\lambda_{KG}}{\lambda_{KP}}\theta_{GE}(e_{G,KE}-e_{G,EL})\right]. \end{aligned}$$

The most notable aspect of this solution is that, as the two output goods become close to perfect substitutes (as $\sigma_u \to \infty$), this expression becomes greatly simplified.[42] All of the terms with the Y constants are eliminated, and the solution is entirely in terms of factor shares (the θ constants). As $\sigma_u \to \infty$,

$$\hat{r} \to \frac{1}{(\theta_{GL}\theta_{PK}-\theta_{GK}\theta_{PL})}\left\{[-\theta_{GK}\theta_{PL}]\hat{\gamma} - \theta_{PL}\hat{\varepsilon} + [-\theta_{GE}\theta_{PL}]\hat{\phi} + [\theta_{GE}\theta_{PL}-\theta_{GL}\theta_{PE}]\hat{\tau}\right\}.$$

42. The limit is evaluated holding fixed all Allen elasticity and factor share and intensity parameters. However, large changes in the substitution elasticity may affect these parameters. For example, as the goods become more substitutable, the price difference, and therefore the difference in production costs net of subsidies, becomes more important. As households shift purchases to the firm producing with lower production costs net of subsidies, the firm uses a greater share of the fixed inputs.

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This result is analogous to equation (12) in Harberger (1962); in that equation when the elasticity of substitution in consumption goes to infinity, the terms with the production elasticities drop out.[43] This extension demonstrates that, like Harberger (1962), our results arise from the fact that only one firm is subsidized. The novel results from our model arise from the inclusion of the third input and the four different policy options (including the labor constraint, which is dropped in this extension).

A.V. Proof of Proposition 2

The Cobb-Douglas assumption implies that all of the cross-price Allen elasticities are equal to one. Further, the own-price elasticities simplify to $e_{M,ii} = (\theta_{Mi} - 1)/\theta_{Mi}$ for $M = G, P$ and $i = K, L, E$ and shares are constant: $\theta_{Gi} = \theta_{Pi} = \theta_i$ for $i = K, L, E$. Imposing these assumptions on equations (3), (4), and (5) and substituting for $\hat{r}$ using equation (2) yields equations (6)–(8).

The sign of the derivatives with respect to the change in the emission tax and the change in the emissions subsidy follow directly from equations (6)–(8). The signs of the derivatives of the change in private and subsidized emissions with respect to the change in the interest subsidy follow directly from equations (6)–(7).

From equation (8) the sign of the derivative of total emissions with respect to the change in the emissions subsidy is positive if and only if $\lambda_{EG} - \lambda_{KG} > 0$. To establish that this condition holds if and only if $\phi > \gamma$ requires an analytical solution of the intensities:

Lemma L1.: Suppose the assumptions of proposition 1 hold, and production is Cobb-Douglas. Then:

$$\frac{K_P}{\bar{K}} = \lambda_{KP} = \frac{\Omega}{1+\Omega}, \quad \frac{K_G}{\bar{K}} = \frac{1}{1+\Omega}, \tag{A20}$$

$$\Omega = \frac{\lambda_{KP}}{\lambda_{KG}} \equiv \left(\frac{(1-\gamma)^{(1-\theta_E)}(1-\phi)^{\theta_E}}{(1+\varepsilon)A_G} \right)^{1/\theta_L} \frac{\bar{L}_P}{\bar{L}_G}, \quad \bar{L}_P = L - \bar{L}_G.$$

$$E_P = \left(\theta_E \left(\frac{\Omega}{1+\Omega}\bar{K} \right)^{\theta_K} \bar{L}_P^{\theta_L} \right)^{1/(1-\theta_E)} \tau^{-1/(1-\theta_E)}, \tag{A21}$$

$$E_G = \left(\frac{(1+\varepsilon)}{(1-\phi)} \theta_E A_G \left(\frac{1}{1+\Omega}\bar{K} \right)^{\theta_K} \bar{L}_G^{\theta_L} \right)^{1/(1-\theta_E)} \tau^{-1/(1-\theta_E)}. \tag{A22}$$

43. Our model without the labor constraint still differs from Harberger (1962) in that here there are three factors of production rather than two, and here there are four different exogenous ad valorem tax changes rather than only a quantity capital tax change.

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Proof: under the assumption of Cobb-Douglas production, shares are constant: $\theta_{Pi} = \theta_{Gi} = \theta_i$ for $i = K, E, L$. Given the definition of Cobb-Douglas production and constant shares, the input factor demands become:

$$r = q_P \theta_K \frac{P}{K_P},$$

$$r_G = q_G \theta_K \frac{G}{K_G},$$

$$\tau = q_P \theta_E \frac{P}{E_P},$$

$$\tau_G = q_G \theta_E \frac{G}{E_G}.$$

Next, by imposing the normalization $q_P = 1$, the definitions of the prices faced by the subsidized firm, and the definition of Cobb-Douglas production, we can eliminate capital and output prices so that:

$$\frac{K_P^{\theta_K} E_P^{\theta_E} L_P^{\theta_L}}{A_G K_G^{\theta_K} E_G^{\theta_E} L_G^{\theta_L}} = \frac{(1+\varepsilon) K_P}{(1-\gamma) K_G},$$

$$\tau = \theta_E K_P^{\theta_K} E_P^{\theta_E - 1} L_P^{\theta_L},$$

$$\tau = \frac{(1+\varepsilon)}{(1-\phi)} \theta_E A_G K_G^{\theta_K} E_G^{\theta_E - 1} L_G^{\theta_L}.$$

The above three equations, along with the equations governing equilibrium in the capital market, are a system of four equations which solve for K_G, K_P, E_G, and E_P. Substituting in the equilibrium condition in the labor market for L_P then yields (A20)–(A22).

Returning now to the proof of proposition 2, equation (A20) establishes that $\lambda_{KG} = 1/(1+\Omega)$. Further, equations (A21) and (A22) give the solutions for E_G and E_P, which imply that:

$$\lambda_{EG} = \frac{E_G}{E_G + E_P} = \frac{1}{1 + E_P/E_G} = \frac{1}{1 + \left(\Omega^{\theta_K} (L_P/L_G)^{\theta_L} \left(\frac{1-\phi}{(1+\varepsilon)A_G}\right)\right)^{1/(1-\theta_E)}}.$$

Substituting for L_P/L_G using the definition of Ω and repeatedly invoking that the shares sum to one with constant returns to scale yields:

$$\lambda_{EG} = \frac{1-\gamma}{1-\gamma+(1-\phi)\Omega}.$$

It is then straightforward to use the solutions for λ_{EG} and λ_{KG} to show that $\lambda_{EG} - \lambda_{KG} > 0$ if and only if $\phi > \gamma$.

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A.VI. Proof of Proposition 3 and Bounds for Preference-Independent Pareto-Improving Policies

The lower bounds are the conditions for which subsidies and output are negatively related, so that a decrease in subsidies increase output. Equation (9) implies that subsidies and output are negatively related for:

$$\lambda_{KG} \geq \lambda_{KG}^{\min,\gamma} = \lambda_{YG},$$

$$\lambda_{KG} \geq \lambda_{KG}^{\min,\phi} = \frac{1-\theta_E}{\theta_K}\lambda_{YG},$$

$$\lambda_{KG} \geq \lambda_{KG}^{\min,\varepsilon} = \frac{(1-\theta_E)(1-\theta_L)}{\theta_L}\lambda_{YG},$$

$$\lambda_{KG} \geq \lambda_{KG}^{\min,L_G} = \frac{-\Gamma_L\theta_L + (1-\theta_E)(1+\Gamma_L)\lambda_{YG}}{(1+\Gamma_L)\theta_K}.$$

Here $\Gamma_i = \lambda_{iG}/\lambda_{iP}$ is the ratio of subsidized input use or output to private input use or output. The analytical solution of the equilibrium allocations implies $\lambda_{KG} > \lambda_{YG}$, so the first condition is always satisfied.

Similarly, the upper bounds are the conditions for which subsidies and emissions are positively related, so that a decrease in subsidies decreases emissions. From equation (8), the conditions are:

$$\lambda_{KG} \leq \lambda_{KG}^{\max,\gamma} = \lambda_{EG},$$

$$\lambda_{KG} \leq \lambda_{KG}^{\max,\phi} = \frac{(1-\theta_E)(1-\theta_K)}{\theta_E\theta_K}\lambda_{EG},$$

$$\lambda_{KG} \leq \lambda_{KG}^{\max,\varepsilon} = \frac{1-\theta_E}{\theta_L}\lambda_{EG},$$

$$\lambda_{KG} \leq \lambda_{KG}^{\max,L_G} = \frac{-\Gamma_L\theta_L + (1-\theta_E)(1+\Gamma_L)\lambda_{EG}}{(1+\Gamma_L)\theta_K}.$$

Appendix A.V shows that $\lambda_{KG} < \lambda_{EG}$ if and only if $\gamma < \phi$. It is also straightforward to show using the analytical solution in appendix A.VII that $\lambda_{EG} > \lambda_{YG}$. Using this result and that shares sum to one with constant returns implies $\lambda_{KG}^{\min,i} < \lambda_{KG}^{\max,i}$ for all i. Therefore, a region $\lambda_{KG}^{\min,i} < \lambda_{KG} < \lambda_{KG}^{\max,i}$ exists such that a decrease in subsidy i increases output and decreases emissions, which is a preference-independent Pareto-improving policy.

For the emissions tax, equation (8) implies that the change in emissions is always negative for an increase in the emissions tax, while equation (9) shows that the

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change in output is always negative for an increase in the emissions tax. Therefore, a change in emissions taxes cannot both increase output and decrease emissions, so no preference-independent Pareto-improving policy exists for the emissions tax.

A.VII. Proof of Proposition 4

Substituting the resource constraint into the welfare function and maximizing with respect to τ yields the first-order condition:

$$\frac{-U_E[C,E]}{U_c[C,E]} = \frac{G_\tau + P_\tau}{E_{P,\tau} + E_{G,\tau}}.$$

Here G, P, and E are evaluated at their equilibrium values, which are functions of subsidies and the emissions tax. The planner thus chooses a tax rate anticipating the effect on the equilibrium allocations. The proof solves the model analytically for G and P as a function of τ. The analytic derivatives, G_τ, P_τ, $E_{P,\tau}$, and $E_{G,\tau}$, are then used to show the above equation is equivalent to the equation in proposition 4.

The outputs may be written as:

$$G = A_G K_G^{\theta_K} E_G^{\theta_E} \bar{L}_G^{\theta_L},$$

$$= \tau \frac{E_G(\tau)}{\theta_E} \frac{(1-\phi)}{(1+\varepsilon)},$$

$$P = K_P^{\theta_K} E_P^{\theta_E} \bar{L}_P^{\theta_L},$$

$$= \tau \frac{E_P(\tau)}{\theta_E}.$$

Using equations (A21) and (A22), the output derivatives are:

$$G_\tau + P_\tau = \frac{1}{\theta_E}\left(\tau E_{G,\tau}\frac{(1-\phi)}{(1+\varepsilon)} + \tau E_{P,\tau} + \frac{(1-\phi)}{(1+\varepsilon)}E_G + E_P\right).$$

The analytic solutions for emissions (A21) and (A22) further imply:

$$E_{G,\tau} = \frac{-1}{1-\theta_E}\frac{E_G}{\tau},$$

$$E_{P,\tau} = \frac{-1}{1-\theta_E}\frac{E_P}{\tau}.$$

Hence:

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$$G_\tau + P_\tau = \frac{-1}{1-\theta_E}\left(\frac{(1-\phi)}{(1+\varepsilon)}E_G + E_P\right).$$

Thus:

$$\frac{G_\tau + P_\tau}{E_{G,\tau} + E_{P,\tau}} = \tau\left(\frac{\frac{(1-\phi)}{(1+\varepsilon)}E_G + E_P}{E_G + E_P}\right).$$

Next, from the first-order condition of the social planner, we have:

$$\tau^* = \frac{E_G + E_P}{\frac{(1-\phi)}{(1+\varepsilon)}E_G + E_P}\left(\frac{-U_E[C,E]}{U_c[C,E]}\right).$$

From the above equation, clearly τ^* exceeds the marginal damage if and only if either the emissions or output subsidy is positive. It remains to show that the above equation is equivalent to the equation in proposition 4. Substituting in the emissions solutions and canceling like terms gives:

$$\tau^* = \frac{\left(\frac{(1+\varepsilon)}{(1-\phi)}A_G\bar{L}_G^{\theta_L}\right)^{1/(1-\theta_E)} + \left(\Omega^{\theta_K}\bar{L}_P^{\theta_L}\right)^{1/(1-\theta_E)}}{\frac{(1-\phi)}{(1+\varepsilon)}\left(\frac{(1+\varepsilon)}{(1-\phi)}A_G\bar{L}_G^{\theta_L}\right)^{1/(1-\theta_E)} + \left(\Omega^{\theta_K}\bar{L}_P^{\theta_L}\right)^{1/(1-\theta_E)}}\left(\frac{-U_E[C,E]}{U_c[C,E]}\right).$$

$$= \frac{\left(\frac{1+\varepsilon}{1-\phi}A_G\right)^{1/(1-\theta_E)} + \Omega^{\theta_K/(1-\theta_E)}\left(\frac{\bar{L}_P}{\bar{L}_G}\right)^{\theta_L/(1-\theta_E)}}{\left(\frac{1+\varepsilon}{1-\phi}A_G\right)^{\theta_E/(1-\theta_E)} + \Omega^{\theta_K/(1-\theta_E)}\left(\frac{\bar{L}_P}{\bar{L}_G}\right)^{\theta_L/(1-\theta_E)}}\left(\frac{-U_E[C,E]}{U_c[C,E]}\right).$$

Using the definition of Ω to eliminate the labor allocations results in:

$$\tau^* = \frac{\left(\frac{1+\varepsilon}{1-\phi}\right)^{1/(1-\theta_E)} A_G^{1/(1-\theta_E)} + \Omega^{(\theta_K+\theta_L)/(1-\theta_E)}\left(\frac{A_G(1+\varepsilon)}{(1-\gamma)^{(1-\theta_E)}(1-\phi)^{\theta_E}}\right)^{1/(1-\theta_E)}}{\left(\frac{1+\varepsilon}{1-\phi}\right)^{\theta_E/(1-\theta_E)} A_G^{1/(1-\theta_E)} + \Omega^{(\theta_K+\theta_L)/(1-\theta_E)}\left(\frac{A_G(1+\varepsilon)}{(1-\gamma)^{(1-\theta_E)}(1-\phi)^{\theta_E}}\right)^{1/(1-\theta_E)}}\left(\frac{-U_E[C,E]}{U_c[C,E]}\right),$$

$$= \frac{(1+\varepsilon)((1-\gamma)+\Omega(1-\phi))}{(1-\phi)((1-\gamma)+\Omega(1+\varepsilon))}\left(\frac{-U_E[C,E]}{U_c[C,E]}\right).$$

Here the second equality follows since constant returns to scale implies that the shares sum to one. The equation given in proposition 4 then follows since $\Omega = \lambda_{KP}/\lambda_{KG}$.

A.VIII. Calibration

The data in appendix table A1 come from the 2006 China Statistical Yearbook (CSY). The factor share ratios λ_{ij} are calculated directly from these data, for example, $\lambda_{KP} = K_P/K = 59{,}628/143{,}144 = 0.4166$.

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Table A1. Data

Variable	Symbol	Value
SOE value added	Y_G	27,177
Private value added	Y_P	45,010
SOE capital	K_G	83,515
Private capital	K_P	59,628
SOE total employees	L_G	1,875
Private total employees	L_P	5,021
SOE taxes paid	NA	6,220
Private taxes paid	NA	5,298
SOE profits	rk_G	6,520
Private profits	rk_P	8,283
SO_2 emissions	E	855
COD emissions	E	493
Subsidies to loss-making enterprises	S	193

Note.—Data are from the 2006 China Statistical Yearbook, tables 14.4 and 14.8, except: SO_2 emissions, which is from table 12-11; subsidies to loss-making enterprises, which is table 8.2; and COD, which is table 2.11 of the China Environment Yearbook. All numbers are 100 million yuan except total employees which are in 10,000 workers, and emissions which are 10,000 tons. The 2006 yearbook reports data from 2005.

A.VIII.a. Calibration of Policies ϕ, γ, and ε

Calibration of ϕ and γ depends on the functional form of the production function. Assuming Cobb-Douglas production, the firm's first-order conditions (China has production taxes, t, which we add and assume are identical for G and P) imply

$$r = (1-t)F_{K,P} = (1-t)\alpha\left(\frac{Y_P}{K_P}\right),$$

$$r_G = r\frac{1-\gamma}{1-\varepsilon} = F_{K,G} = \alpha(1-t)\frac{Y_G}{K_G},$$

where α is the capital share parameter. We set $\varepsilon = 0$, since some argue in China that actually SOEs are forced to sell at below market prices. These equations may then be combined to get

$$\gamma = 1 - \frac{K_P Y_G}{Y_P K_G} = 0.57.$$

Similarly, for ϕ,

$$\phi = 1 - \frac{E_P Y_G}{Y_P E_G} = 1 - \frac{\sigma_P}{\sigma_G}.$$

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Table A2. Simulation—Wider Variation in Allen Elasticities

	A. Parameter Values			
	$e_{P,KE}$	$e_{P,EL}$	$e_{G,KE}$	$e_{G,EL}$
1 (base case)	.5	.3	.5	.3
2	2	.3	.5	.3
3	.5	2	.5	.3
4	.5	.3	2	.3
5	.5	.3	.5	2
6	−.5	.3	.5	.3
7	.5	0	.5	.3
8	.5	.3	−.5	.3
9	.5	.3	.5	0

	B. Simulation Results							
	$\hat{\gamma}$ = 10%				$\hat{\varepsilon}$ = 10%			
	$\hat{r}$	$\hat{w}$	$\hat{E}_P$	$\hat{E}_G$	$\hat{r}$	$\hat{w}$	$\hat{E}_P$	$\hat{E}_G$
1	5.45%	−2.32%	−.83%	.33%	5.45%	−2.32%	−.83%	3.69%
2	5.45%	−2.32%	1.61%	.33%	5.45%	−2.32%	1.61%	3.69%
3	5.45%	−2.32%	−3.60%	.33%	5.45%	−2.32%	−3.60%	3.69%
4	5.45%	−2.32%	−.83%	−.89%	5.45%	−2.32%	−.83%	5.16%
5	5.45%	−2.32%	−.83%	1.72%	5.45%	−2.32%	−.84%	19.03%
6	5.45%	−2.32%	−2.46%	.33%	5.45%	−2.32%	−2.46%	3.69%
7	5.45%	−2.32%	−.35%	.33%	5.45%	−2.32%	−.35%	3.69%
8	5.45%	−2.32%	−.83%	1.15%	5.45%	−2.32%	−.83%	2.72%
9	5.45%	−2.32%	−.83%	.09%	5.45%	−2.32%	−.83%	.99%

	C. Simulation Results							
	$\hat{\phi}$ = 10%				$\hat{\bar{L}}_G$ = 10%			
	$\hat{r}$	$\hat{w}$	$\hat{E}_P$	$\hat{E}_G$	$\hat{r}$	$\hat{w}$	$\hat{E}_P$	$\hat{E}_G$
1	.00%	.00%	.00%	3.36%	6.56%	−2.79%	−4.74%	9.52%
2	.00%	.00%	.00%	3.36%	6.56%	−2.79%	−1.80%	9.52%
3	.00%	.00%	.00%	3.36%	6.56%	−2.79%	−8.07%	9.52%
4	.00%	.00%	.00%	6.05%	6.55%	−2.79%	−4.74%	11.28%
5	.00%	.00%	.00%	17.31%	6.56%	−2.79%	−4.74%	7.52%
6	.00%	.00%	.00%	3.36%	6.56%	−2.79%	−6.70%	9.52%
7	.00%	.00%	.00%	3.36%	6.56%	−2.79%	−4.15%	9.52%
8	.00%	.00%	.00%	1.56%	6.56%	−2.79%	−4.74%	8.34%
9	.00%	.00%	.00%	.90%	6.56%	−2.79%	−4.74%	9.87%

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Table A2 (*Continued*)

	D. Simulation Results									
	$\hat{\gamma} = 10\%$		$\hat{\varepsilon} = 10\%$		$\hat{\phi} = 10\%$		$\widehat{\overline{L}}_G = 10\%$		$\hat{\tau} = 10\%$	
	$\hat{E}$	$\hat{Y}$	$\hat{E}$	$\hat{Y}$	$\hat{E}$	$\hat{Y}$	$\hat{E}$	$\hat{Y}$	$\hat{E}$	$\hat{Y}$
1	.04%	−.54%	2.57%	−.54%	2.52%	.00%	5.97%	.30%	−3.42%	.00%
2	.65%	−.54%	3.17%	−.54%	2.52%	.00%	6.70%	.30%	−4.54%	.00%
3	−.65%	−.54%	1.88%	−.54%	2.52%	.00%	5.14%	.30%	−6.39%	.00%
4	−.88%	−.54%	3.67%	−.54%	4.54%	.00%	7.29%	.30%	−5.44%	.00%
5	1.09%	−.54%	14.08%	−.53%	13.00%	.00%	4.46%	.30%	−13.89%	.00%
6	−.36%	−.54%	2.16%	−.54%	2.52%	.00%	5.48%	.30%	−2.67%	.00%
7	.16%	−.54%	2.69%	−.54%	2.52%	.00%	6.11%	.30%	−2.89%	.00%
8	.66%	−.54%	1.83%	−.54%	1.17%	.00%	5.08%	.30%	−2.07%	.00%
9	−.14%	−.54%	.53%	−.54%	.67%	.00%	6.23%	.30%	−1.57%	.00%

Note.—Panel A shows the parameter values used in simulations 1 through 9. All other parameter values remain at their base case values (table 3). Panels B and C show simulation results for four endogenous variables ($\hat{r}$, $\hat{w}$, $\hat{E}_P$, and $\hat{E}_G$) in response to one of four exogenous policy changes. Panel D shows simulation results for total emissions ($\hat{E}$) and total output ($\hat{Y}$) in response to the same four policy changes, plus a change in the emissions tax ($\hat{\tau}$).

Here σ is the emissions intensity of output. Bajona and Kelly (2012) estimates $\sigma_G/\sigma_P = 5$ for SO_2 and Wang and Wheeler (2003) estimate it at 5.7 for chemical oxygen demand (COD).

A.VIII.b. Construct τ, E_G

Since only total emissions data are available, we use the emissions ratios to construct emissions by sector.

$$\frac{\sigma_G}{\sigma_P} = \frac{E_G}{E_P}\frac{Y_P}{Y_G} = \frac{E_G}{1 - E_G}\frac{Y_P}{Y_G}$$

$$E_G = \frac{(\sigma_G/\sigma_P)Y_G E}{Y_P + (\sigma_G/\sigma_P)Y_G}.$$

This gives emissions of $E_G = 642$ for SO_2 and $E_G = 382$ for COD.

Wang and Wheeler (2005, n. 13) reports that τ equals 0.5 yuan/kilogram for COD and 0.4 for SO_2. This corresponds to 0.05 100M yuan per 10K metric tons for SO_2 and 0.04 for COD.[44]

44. The emissions tax revenue does not measure all spending on environmental regulations, but total environmental compliance spending is still small relative to GDP.

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A.VIII.c. Construct r, Total Subsidies

To get the interest rate, we need to compute depreciation as depreciation is included in value added but not profits. Assuming a depreciation rate of $\delta = 0.06$, we have:

$$DEP_G = \delta K_G = 5,011$$

and the same for private. The interest rate is then

$$r = \frac{rk}{k} = \frac{\pi_G + \pi_P + DEP_G + DEP_P}{K_G + K_P} = 0.16.$$

This is a high interest rate, but probably not unreasonable given China's very fast economic growth. We add depreciation to capital income in all the calculations below.

We now construct capital and emissions subsidies:

$$\gamma r K_G = 7,764,$$

$\phi \tau E_G = 21$ for SO_2, $= 16$ for COD.

A.VIII.d. Calibration of Wages

We have from the profit equations (including a tax t on value added):

$$\pi_G = (1 - t)F(K_G, L_G, E_G) - r_G K_G - wL_G - \tau_G E_G + S.$$

Assuming after-subsidy profits equal zero, we have:

$$\begin{aligned} wL_G &= (1 - t)F(K_G, L_G, E_G) - r_G K_G - \tau_G E_G + S \\ &= Y_G - tY_G - rK_G + \gamma r K_G - \tau E_G + \phi \tau E_G + S \\ &= 27,177 - (6,220 - 0.05 \cdot 642) + 7,764 - 0.05 \cdot 642 + 21 + 193 = 17,404. \end{aligned}$$

This assumes that the environmental taxes are counted in the data on total taxes paid. The private data wage equation is the same equation with no subsidies, which results in $wL_P = 27,852$. The calibration is slightly different using COD instead of SO_2.

Given the wage data, we have

$$S = wL_G - w_G L_G = 17,211.$$

A.VIII.e. Calibration of Shares

We calibrate the shares using the standard assumption that tax income is allocated proportionally to each factor according to their factor shares. For private shares, we have

$$\theta_{PK} Y_P = rK_P + \theta_{PK}(taxes - env.taxes_P)$$

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$$\theta_{PK} = \frac{rK_P}{Y_P - (taxes - env.taxes_P)}$$

$$\theta_{PK} = \frac{11,860}{45,010 - 5,298 + \tau E_P} = 0.2986.$$

Similarly,

$$\theta_{PL} = \frac{wL_P}{Y_P - (taxes - env.taxes_P)} = 0.7012$$

$$\theta_{PE} = \frac{\tau E_P}{Y_P - (taxes - env.taxes_P)} = 0.0002.$$

This is the calibration for SO_2; the values for COD are only slightly different.

For the subsidized firm, we must also include the subsidy revenue.

$$\begin{aligned}\theta_{GK} Y_G &= r_G K_G = rK_G - \gamma r K_G \\ &= profits + depreciation + \theta_{GK}(taxes - env.taxes_G) - \gamma r K_G\end{aligned}$$

$$\theta_{GK} = \frac{rK_G - \gamma r K_G}{Y_G - (taxes - env.taxes_G)}$$

$$\theta_{GK} = \frac{11,531 - 7,764}{27,177 - 6,220 + 21} = 0.1795.$$

The share for G is lower, but this is a comparison of apples to oranges. rK_G/Y_G is 0.55, which is higher than private as expected since SOEs tend to be more capital intensive.

Similarly,

$$\theta_{GE} = \frac{\tau E_G - \phi \tau E_G}{Y_G - (taxes - env.taxes_G)} = 0.0002$$

$$\theta_{GL} = \frac{w_G L_G}{Y_G - (taxes - env.taxes_G)} = 0.8202.$$

We report only four significant digits, so the sum of shares differs slightly from one due to rounding.

A.IX. Numerical Simulations of Model Extensions

Here we extend the simulations to the more general models presented in appendix A.IV in which the two goods are imperfect substitutes and where there is no labor constraint. Appendix table A3 presents the results when the goods are imper-

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Table A3. Simulation with Imperfect Substitutes

A. Parameter Values

	σ_u
1 (base case)	∞
2	.1
3	.5
4	1
5	2
6	10

B. Simulation Results

	$\hat{\gamma} = 10\%$				$\hat{\varepsilon} = 10\%$			
	$\hat{r}$	$\hat{w}$	$\hat{E}_P$	$\hat{E}_G$	$\hat{r}$	$\hat{w}$	$\hat{E}_P$	$\hat{E}_G$
1	5.45%	−2.32%	−.83%	.33%	5.45%	−2.32%	−.83%	3.69%
2	2.05%	−.87%	−.31%	−1.97%	2.05%	−.87%	−.31%	1.39%
3	4.09%	−1.74%	−.63%	−.59%	4.09%	−1.74%	−.63%	2.77%
4	4.67%	−1.99%	−.72%	−.19%	4.67%	−1.99%	−.72%	3.17%
5	5.03%	−2.14%	−.77%	.05%	5.03%	−2.14%	−.77%	3.41%
6	5.36%	−2.28%	−.82%	.27%	5.36%	−2.28%	−.82%	3.63%

C. Simulation Results

	$\hat{\phi} = 10\%$				$\hat{\bar{L}}_G = 10\%$			
	$\hat{r}$	$\hat{w}$	$\hat{E}_P$	$\hat{E}_G$	$\hat{r}$	$\hat{w}$	$\hat{E}_P$	$\hat{E}_G$
1	.00%	.00%	.00%	3.36%	6.56%	−2.79%	−4.74%	9.52%
2	.00%	.00%	.00%	3.36%	−22.98%	9.79%	−.21%	−10.51%
3	.00%	.00%	.00%	3.36%	−5.24%	2.23%	−2.93%	1.52%
4	.00%	.00%	.00%	3.36%	−.18%	.08%	−3.71%	4.95%
5	.00%	.00%	.00%	3.36%	2.93%	−1.25%	−4.18%	7.06%
6	.00%	.00%	.00%	3.36%	5.78%	−2.46%	−4.62%	8.99%

Note.—Panel A shows the parameter values for σ_u used in the simulations. All other parameter values remain at their base case values (table 3, and row 1 of table 4). Panels B and C show simulation results for four endogenous variables ($\hat{r}$, $\hat{w}$, $\hat{E}_P$, and $\hat{E}_G$) in response to one of four exogenous policy changes.

fect substitutes (but there is still a labor constraint). All of the parameters, including the substitution elasticities, are kept at the base case value, except that we now vary the substitution elasticity σ_u (in the base case of the original model, this was infinite, that is, $\sigma_u = \infty$). When this elasticity is high ($\sigma_u = 10$, row 6), all of the results are very similar to their base-case values (for instance, a 10% increase in the capital subsidy increases the capital price by 5.36% instead of 5.45% as in the base case). For

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smaller values of σ_u, the incidence and environmental effects of the capital subsidy γ and the output subsidy ε are moderated. As σ_u becomes smaller (i.e., as the two goods become worse substitutes), the magnitudes of both the input price changes ($\hat{r}$ and $\hat{w}$) and emissions changes ($\hat{E}_P$ and $\hat{E}_G$) become smaller but do not change sign. The exception is the effect of the capital subsidy γ on emissions in the subsidized firm—with a small enough σ_u this can change from slightly positive to negative.

In appendix table A4, we simulate the model in which there is no labor constraint and the two goods are imperfect substitutes. We set the elasticity of substitution in consumption equal to 1; all other parameters are kept at the base case values, but we vary the production elasticities. These results can thus be compared to row 4 in appendix table A3 (where $\sigma_u = 1$). The removal of the labor constraint does not sub-

Table A4. Simulation without Labor Constraint, with Imperfect Substitutes

	A. Parameter Values			
	$e_{P,KE}$	$e_{P,EL}$	$e_{G,KE}$	$e_{G,EL}$
1 (base case)	.5	.3	.5	.3
2	0	.74	0	.74
3	.5	.3	0	.74
4	0	.74	.5	.3

	B. Simulation Results							
	$\hat{\gamma} = 10\%$				$\hat{\varepsilon} = 10\%$			
	$\hat{r}$	$\hat{w}$	$\hat{E}_P$	$\hat{E}_G$	$\hat{r}$	$\hat{w}$	$\hat{E}_P$	$\hat{E}_G$
1	4.66%	−1.98%	−1.06%	.28%	4.54%	−1.93%	−3.52%	6.91%
2	4.66%	−1.98%	−2.37%	.04%	4.54%	−1.93%	−4.79%	5.81%
3	4.66%	−1.98%	−1.06%	.04%	4.54%	−1.93%	−3.52%	5.81%
4	4.66%	−1.98%	−2.37%	.28%	4.54%	−1.93%	−4.79%	6.91%

	C. Simulation Results			
	$\hat{\phi} = 10\%$			
	$\hat{r}$	$\hat{w}$	$\hat{E}_P$	$\hat{E}_G$
1	.00%	.00%	.00%	3.36%
2	.00%	.00%	.00%	6.07%
3	.00%	.00%	.00%	6.07%
4	.00%	.00%	.00%	3.36%

Note.—Panel A shows the parameter values used in simulations 2 through 5. All other parameter values remain at their base case values (table 3), and the elasticity of substitution between the two output goods σ_u is kept at 1. Panels B and C show simulation results for four endogenous variables ($\hat{r}$, $\hat{w}$, $\hat{E}_P$, and $\hat{E}_G$) in response to one of three exogenous policy changes.

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stantially affect the incidence results $\hat{r}$ and $\hat{w}$: they are still invariant to the production substitution elasticities and of a similar magnitude. The emissions changes are of a larger magnitude in table A4 than in row 4 of table A3—without the labor constraint binding the subsidized firm's labor input, the emissions input is given more freedom to change, which it does. For instance, for a 10% output subsidy increase ($\hat{\varepsilon} = 10\%$), the private firm's emissions reduction increases from 0.72% to 3.52%, and the subsidized firm's emissions increase rises from 3.17% to 6.91%. Without a labor constraint, the pollution tax subsidy ϕ has nearly the same incidence and environmental effects as in the base case.

Appendix tables A3 and A4 demonstrate that our results do not depend on the assumption of identical output goods nor on the labor constraint. Therefore, the analytical and numerical results from our models can also apply to cases where goods are imperfect substitutes and subsidies are not associated with hiring restrictions.

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