Are Carbon Taxes More Efficient in Industrializing Countries? Comparing China and India to the United States

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Abstract

Conventional wisdom holds that, without considering environmental benefits, a carbon tax would reduce economic welfare. As a result, industrializing countries often enter climate change negotiations with demands for special treatment. We re-examine gross welfare costs, demonstrating how three factors in the literature combine to importantly reduce the welfare cost of a revenue-neutral carbon tax, and that this effect is especially important in developing economies. Incorporating informal production, tax evasion, and untaxed Ricardian rents, we conduct numerical simulations of carbon taxes in the two largest developing countries, China and India, as well as in the United States. Overall, efficiency costs are negative in all three countries for an important range of reductions. Employing a carbon tax is in fact cheaper than existing tax policy. Moreover, because of the importance of the three factors in industrializing countries, the gross costs of carbon tax policy are lower in China and India than in the U.S. Our results should extend to the tax systems in many developing economies.

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1 Introduction

The existing economics literature has long held that instituting a carbon tax trades higher environmental quality for lower economic welfare, even when the revenue raised from pricing carbon is completely recycled to reduce pre-existing distortionary taxes.[1] This tradeoff represents a rejection of the popular conjecture known as the double dividend hypothesis, whereby it is possible to simultaneously improve environmental quality through the use of carbon pricing while increasing non-environmental aspects of economic welfare by decreasing distortionary taxes on desirable activities such as the supply of capital and labor. Underlying this result is the tax interaction effect: increased deadweight loss when new taxes are levied on already-taxed commodities means that narrowly based taxes, for example on fossil fuels, are less efficient than taxes on broad sectors of the economy. Parry et al (2012) provide a clear statement of the consensus among economists: "The general finding in the theoretical literature is that—with some qualifications—the net impact from shifting taxes off income and onto emissions is to increase the costs of preexisting taxes." In other words, a strong double dividend does not occur.[2] A direct consequence of this finding is that the (second best) optimal environmental tax is less than the classic textbook level of marginal external pollution damages.

Because carbon taxes are believed to hurt economic welfare (ignoring environmental externalities), industrializing countries hoping to continue their current growth trajectories have insisted on transfer mechanisms and other forms of special treatment as international climate change goals are negotiated. For example, the Kyoto Protocol

[1] We refer to the carbon price throughout as a tax, though in practice the policy options are broader since similar results can be obtained using a cap and trade system if the government collects and recycles the revenue from sale of carbon permits.

[2] The "strong double dividend," as defined in Goulder (1995), is the existence of negative gross costs when a revenue-neutral environmental tax is substituted for a representative distortionary tax.

and Paris Agreement set up the Clean Development Mechanism and the Sustainable Development Mechanism, respectively, to facilitate transfers between developed and industrializing countries.

We re-examine the conclusion that carbon taxes must hurt gross economic welfare (that is, economic welfare ignoring environmental benefits) by noting that earlier findings[3] were largely developed under the implicit assumption that tax systems were optimal or close to optimal to begin with. By contrast, tax systems in the real world contain unnecessary distortions and these distortions are particularly pronounced in developing countries. If the status quo tax system is not optimal, introducing a carbon pricing policy can potentially counteract pre-existing distortions in a country's tax system. In other words, a carbon tax could be a better (less distortionary) way to raise revenue than some other approaches currently being taken.

We focus on three tax distortions discussed in the theoretical literature. Each is more prominent in developing countries than in OECD countries: (1) The presence of an informal sector that does not pay any taxes. Bento et al. (2018) show how carbon taxes tend to fall on goods that have poor substitutes in the informal sector: when carbon taxes are used to (partially) replace taxes on formal-sector labor and capital the size of the informal sector shrinks, broadening the tax base and improving economic outcomes. (2) Wasteful tax evasion.[4] Metcalf and Weisbach (2009) and Liu (2013) argue that taxes on carbon are much harder to evade than most other taxes. This is

[3] Bovenberg and Goulder (1996), Bovenberg and de Mooij (1994), Goulder (1995), Parry (1995), Fullerton and Metcalf (2001), Bovenberg and Goulder (2002), Goulder and Williams (2003).

[4] Informal sector production and formal sector tax evasion are related in spirit, but kept distinct in the development and public finance literatures. In the context of carbon pricing, Bento et al. (2018) distinguish between these distortions, pointing out three differences. First, the informal economy and tax evasion are empirically separable (Schneider and Enste 2011). Second, informal economy and tax evasion are generated in very different parts of the income distribution (Johns and Slemrod 2010). Third, the mechanisms for how these distortions are modeled are separate (Bento et al. and Liu 2013).

For our purposes here we note that our results are robust to relabeling, and that we take a conservative empirical approach in order to avoid any potential for double counting (see footnote 8 in the model setup).

because only a small number of firms (e.g., oil refineries and power plants) need to be monitored to collect a carbon tax, making evasion much more difficult than when taxes must be collected from all firms, even very small ones. Thus, a carbon tax diminishes incentives to evade. (3) Many developing countries depend heavily on the extraction of exhaustible resources. Bento and Jacobsen (2007) show how the presence of Ricardian rents, which accrue to these resources, can lower the cost of reform because carbon taxes act as surrogate taxes on rents.

We show how these three features interact in different combinations in the context of a standard analytical model used to assess the impacts of a carbon tax on gross economic welfare. We select three countries to examine in detail: China, India, and the United States. Together, these three countries are responsible for about 50% of the world's carbon emissions (Olivier et al. 2016). For most of the post-World War II period, the U.S. was the leading emitter but China passed the U.S. roughly a decade ago (Auffhammer and Carson (2008)). China will account for 25% of the world's projected increase in carbon emissions between 2012 and 2040, with India accounting for another 20% (EIA (2016)).

We first show in a simple baseline—not considering any of the three factors above—that a revenue-neutral carbon tax swap conforms to the standard theoretical prediction that it would reduce economic growth in China, India and the U.S. over the entire range of emission reduction scenarios. Further, since China's economy has more heavy industry, and its energy mix is also more carbon-intensive per unit, the negative impact for a given reduction in emissions in China is substantially larger than it is for the U.S.[5]

[5]Paltsev et al. (2007) review results from the MIT EPPA model and find relative energy emissions intensity is a key factor determining how countries will bear cost of reducing carbon emissions. Surprisingly few papers directly compare the cost of climate change reform in China and the U.S. An exception is Paltsev et al. (2015) who introduce a global carbon tax into the MIT Integrated Earth System Model targeted at stabilizing radiative forcing to 4.5 W/m^2. They predict the decrease in GDP growth for China as a result of policy to be roughly double that of the U.S. by 2050. Our setting here, while empirically much simpler, replicates this result in the baseline.

India's energy intensity is between that of China and the U.S. and so the drag on its economy from implementing carbon pricing in the simple baseline is also intermediate.

We next explore the role of informal production, tax evasion, and resource rents in these three countries using plausible values for key parameters drawn from the relevant literatures. We examine how each factor separately, and when interacted with the others, changes the economic cost of environmental tax reform. Our simulations produce two key results. First, gross welfare cost—not accounting for environmental improvement—is negative for emissions cuts of 10% in all three countries. In other words, the baseline cost of cutting carbon emissions is more than fully offset by the three factors. Second, China and India have considerably more to gain from carbon tax reform than the U.S.: Even though these two economies have greater energy intensities (dramatically so in the case of China), the cost of a carbon tax, expressed as a fraction of GDP, is actually lower in China and India than it is in the U.S. for emissions reductions up to 12%. This reverses the cost ordering in the baseline.

A number of other industrializing countries also have large informal economies, high rates of formal sector tax evasion, and rely heavily on exhaustible resources, suggesting these results may apply more broadly. Likewise, results from the U.S. example are likely in line with some other OECD countries, for example Australia and Canada, that have often been reluctant participants in climate negotiations. Another range of OECD countries, for example Denmark and Japan, have very small informal sectors, low tax evasion, and few fossil fuel resources. Effects in these countries may best correspond to a baseline case where a strong double dividend does not occur.

Our simulations are stylized representations and so not intended to produce precise estimates of the costs of a revenue-neutral carbon tax; this would require country-specific modeling with fine sectoral and administrative detail. However, we think that the results here argue strongly for the inclusion of the three tax effects we study in richer tax models: We demonstrate the existence of negative gross costs (a "strong double dividend") of implementing a carbon tax in what are arguably the three most important economies for climate change policy. This is of critical importance given the deeply ingrained beliefs by the leaders of major developing countries that pricing carbon will hurt their economies. Surprisingly it is the developing countries, which tend to have a confluences of the three factors analyzed here,[6] that may in fact have more to gain from reforming their tax systems toward a carbon tax than would many OECD countries.

Our results are subject to some important caveats: First, our model is static in nature and cannot account for the dynamic effects of innovation and technological change. It also does not account for international trade; specific types of firms, individuals, and subnational regions are likely to suffer significant losses from implementation of a carbon tax. As such, they are likely to fight a carbon tax, raising political economy issues (to do with the handling of carveouts and compensation) that we do not consider here and that would reduce the efficiency of a tax.

The rest of the paper is organized as follows: Section 2 describes the analytical framework and shows how an informal economy, tax evasion, and Ricardian rents can be added. Section 3 presents the numerical model, discusses calibration, and presents estimates of the magnitudes of the effects. Section 4 provides discussion.

[6]Developing countries have larger informal economies: Schneider (2005) finds that the unweighted average size of the informal economy in 21 OECD countries is 16.8% of GDP. In Asia, Central and South American, and Africa, the sizes of the informal economy are 28.5%, 41.1%, and 41.3%, respectively. They rely more on resource rents. For OECD countries, resource rents averaged 1.3% of GDP between 1971 and 2008. For non-OECD countries, resource rents averaged 10.4% of GDP (authors' calculations). They also have higher levels of tax evasion: Of the top 30 carbon emitting countries, 14 are OECD countries and have an average self-employment rate of 13.4%. The remaining developing countries have a self-employment rate of 28.9% (Liu 2013).

2 Analytical Model

Our starting point is a standard optimal tax model used in the literature to examine the cost of moving the tax base toward a carbon-emitting fossil energy sector.[7] Developing countries have tax systems that deviate sharply from the assumptions of this neoclassical, optimal tax model. Here we incorporate three of them into a single analytical framework. First we allow for the presence of an informal sector (Bento et al. (2018)). Second, we incorporate a fixed factor in the production of fossil energy (Bento and Jacobsen (2007)). Third, we incorporate tax evasion (Liu (2013)).[8]

2.1 Firms

There are four types of firms: manufactured goods producers G, formal services S^F, informal services S^I, and fossil energy producers E.

2.1.1 Manufacturing and Services

Manufacturing and service firms are distinguished in that informal production S^I can substitute for formal services S^F, but not for manufactured goods G.

Manufactured goods are produced using labor L_G and fossil energy E_G with constant returns to scale:

$$G = G\left(L_G, E_G\right). \tag{1}$$

Firms producing formal sector services S^F use labor L_{SF} and fossil energy E_{SF}

[7]See Gordon and Nielsen (1997), and Williams (2003).

[8]In the numerical simulation, we handle the potential overlap between tax evasion and the informal sector by conservatively assuming that all informal sector activity is already counted in estimates of tax evasion; we deduct these sectors entirely from aggregate evasion estimates in order to avoid the potential for double counting.

using constant returns to scale technology:

$$S^F = S_F\left(L_{SF}, E_{SF}\right). \tag{2}$$

The Informal Economy The third type of firm produces informal services S^I using labor L_{SI} and energy E_{SI}. In contrast to the other sectors, marginal cost is assumed to be increasing, resulting in an upward sloping supply curve. As the informal sector scales up, it requires more infrastructure, becomes a greater target of government scrutiny, and generally becomes more difficult to hide.

Informal sector production is represented by:

$$S^I = \left(L_{SI}\right)^{\theta_L}\left(E_{SI}\right)^{\theta_E}, \tag{3}$$

where θ_L and θ_E are parameters and $0 < \theta_L + \theta_E < 1$. Together they control the returns to scale in production of informal services and the slope of the marginal cost curve.

We combine the rising marginal cost curve with the assumption that formal sector services S^F and informal sector services S^I are perfect substitutes in consumption. These assumptions create the mechanism governing the size of the informal sector: Consumers purchase informal services while they are cheap, tracing the supply curve until they match the price of services in the formal sector. θ_L and θ_E thus control the degree to which informal production is important in an economy.[9]

[9]Since the price of informal services is greater than their marginal cost, firms in the informal sector accumulate profits. These are not pivotal to welfare calculations, but we nevertheless account for them in general equilibrium:

$$\pi_{SI} = \int\int \left[p_{SI} - MC\right] dL_{SI} dE_{SI}.$$

2.1.2 Fossil Energy Firms

The final firm type produces fossil energy, used only as an intermediate good in production:

$$E = E_G + E_{SF} + E_{SI}. \tag{4}$$

By construction, each unit of fossil energy E generates one unit of carbon,[10] making taxes on fossil energy or carbon equivalent. The production function $E(.)$ is constant returns to scale with two inputs:

$$E = E(L_E, F), \tag{5}$$

labor L_E and a fixed factor F, generating the rents explained in more detail below.

Fossil energy firms are taxed in two ways. First, they must pay a tax on labor, τ_L. Second, they pay a carbon tax proportional to energy production, τ_E. Workers receive an after-tax wage normalized to 1, so the cost of wages to firms is $1 + \tau_L$.

Ricardian Rents The fixed factor is modeled as an immobile resource that is used intensively in the production of fossil energy, such as coal, natural gas, and oil (Bento and Jacobsen (2007)). Production of the fixed factor is not competitive, resulting in Ricardian rents accruing to the owners. An optimal tax system would fully tax away Ricardian rents without distorting behavior. The (lower) pre-existing tax on extraction is τ_F and we assume it is held fixed throughout.

[10]It is possible to specify a clean energy input in the analytical model. This would be equivalent to the present setup if clean energy appeared as part of the L_{G} input; in this case the substitution elasticity would become a composite that included a component reflecting substitution across energy types. Since we do not explicitly consider subsidies to green energy in the present setup, we abstract from defining a separate sector.

2.2 Government

The government collects three forms of taxes: labor taxes τ_L, fossil energy or carbon taxes τ_E (the two are equivalent in this setting), and extraction taxes on the fixed factor τ_F. The collection of taxes is not complete, but instead suffers from the pervasive phenomenon of tax evasion.

Tax Evasion Tax τ_i with $i \in \{L, E\}$ may be evaded at rate ϵ_i. An evasion rate of 1 means that no taxes are paid. Since all taxes are levied on firms in this model, only firms evade taxes.

If a tax is evaded, the firm must pay an increasing and convex per-unit cost $\gamma_i(\epsilon_i)$. If a firm pays this cost, we assume it will not be penalized for avoiding the tax.

Under this setup, firms set the marginal cost of avoiding a tax levied at rate τ_i equal to the marginal benefit of doing so:

$$\frac{d\gamma_i(\epsilon_i)}{d\epsilon_i} = \tau_i. \tag{6}$$

Without loss of generality, the extraction tax τ_F is assumed to be paid with perfect honesty. Since the government policy does not adjust the extraction tax, the evasion rate does not change either, and the rate τ_F represents the effective rate of tax combining both the statutory rate and the rate of evasion.

Government revenue H reflects taxes actually paid:

$$H = (1 - \epsilon_E)\,\tau_E E + \sum_{i=G,S_M,E} (1 - \epsilon_L)\,\tau_L L_i + \tau_F F. \tag{7}$$

2.3 Households

A representative household buys all goods and services, supplies labor, and captures residual profits from firms.

Direct utility comes from the two final products (manufactured goods G and services S) and from consumption of leisure (l). Services are a combination of formal services and informal services:

$$S = S^F + S^I. \tag{8}$$

Since informal services and formal services are perfect substitutes, they have the same price:

$$p_S \equiv p_{SI} = p_{SF}. \tag{9}$$

Leisure is equal to the time endowment $\left(\overline{L}\right)$ less the labor supply (L). Households suffer disutility from pollution related to the production of fossil energy; this can include carbon and also local pollutants in the air and water. The disutility given by $\phi(E)$ is assumed to be weakly convex.

The utility function from non-environmental goods, $u(.)$, is assumed to be quasi-concave. The overall household utility function is:

$$U = u\left(G, S, \overline{L} - L\right) - \phi(E). \tag{10}$$

There are four sources of income for households. First is labor; the after-tax wage is normalized to 1. Second are lump-sum transfers from government. Third are profits from the household's ownership of the fixed factor F. Fourth are profits from ownership of informal firms. The household budget constraint is:

$$p_G G + p_S S = L + H + \pi_{FF} + \pi_{SI}. \tag{11}$$

2.4 Prices

We normalize the after-tax wage 1, the cost of labor to firms, after accounting for the labor tax and evasion of that tax, is $p_L = 1 + (1 - \epsilon_L(\tau_L))\tau_L + \gamma_L(\tau_L)$. We define the market price of energy as p_E. Markets for energy, manufactured goods, and services are competitive and firms earn no profits.

Production of the manufactured good occurs with constant returns to scale and with only inputs L_G and E. As a result, the profitability function of the manufactured good is:

$$\pi_G = p_G G - p_L L_G - p_E E_G. \tag{12}$$

Similarly, the profitability of formal sector services firms is given by:

$$\pi_{SF} = p_S S^F - p_L L_{SF} - p_E E_{SF}. \tag{13}$$

Firms producing informal services do not pay taxes on their labor, but still buy energy at market prices:

$$\pi_{SI} = p_S S^I - L_{SI} - p_E E_{SI}. \tag{14}$$

Energy firms produce using labor and the fixed factor. They must pay taxes on labor, the carbon tax, and the tax on the fixed factor. This implies a profitability function of:

$$\pi_E = (p_E - (1 - \epsilon_E)\tau_E - \gamma_E(\tau_E))E - p_L L_E - (\tau_F F + \pi_{FF}). \tag{15}$$

If p_E is the market price of fossil energy, $(p_E - (1 - \epsilon_E)\tau_E - \gamma_E(\tau_E))E$ is the after-tax amount of revenue earned by producers, accounting for both the carbon tax and evasion of that tax. Owners of the fixed factor charge prices which make producers just indifferent to shutting down, so fossil energy rents π_{FF} are given by:

$$\pi_{FF} = \left(p_E - \left(1 - \epsilon_E\right)\tau_E - \gamma_E\left(\tau_E\right)\right)E - p_L L_E - \tau_F F. \tag{16}$$

2.5 Welfare Analysis

We derive the change in welfare arising from an increase in the carbon tax (equivalent to a fossil energy tax here) combined with a revenue-neutral reduction in the labor tax. This amounts to a tilt on the margin toward an carbon tax and away from a labor tax, where τ_E and τ_L below represent the initial levels of the two taxes.

To provide intuition on the source of effects, the welfare measure can be decomposed into the following components (see appendix for details):

$$\begin{aligned}\frac{1}{\lambda}\frac{dW}{d\tau_E} = &\left[\left(\frac{\phi'}{\lambda} - \left(1-\epsilon_E\right)\tau_E - \gamma_E\right)\left(-\frac{dE}{d\tau_E}\right)\right] + \left[\left(1-\epsilon_L\right)\tau_L \frac{d\left(L - L_{SI}\right)}{d\tau_E}\right] \\ &+ \left[\left(L - L_{SI}\right)\gamma_L' + E\gamma_E' - \epsilon_L'\tau_L\left(L - L_{SI}\right) - \epsilon_E'\tau_E E\right] - \left[\frac{d\pi_{FF}}{d\tau_E}\right]\end{aligned} \tag{17}$$

The first bracketed term balances the welfare gain from reduced pollution, ϕ', against the primary cost of increased distortion in energy markets (where the primary cost is proportional to the pre-existing tax wedge on energy). The benefit from reduced pollution is assumed to be zero in our primary calculations of the change in economic welfare abstracting from environmental benefits. If starting from a situation with no carbon tax the primary costs go to zero on the margin, leaving only the gain from improved environmental quality in this first term.[11]The second bracketed term is the tax base effect on labor, the primary factor of production. This includes both a “revenue

[11]For non-marginal carbon taxes, the primary costs increase with energy intensity, and so will likely be larger in developing economies like China. We explore this in detail in the simulation below.

recycling effect" and a "tax interaction effect" (Goulder (1995)). The revenue recycling effect is the benefit obtained by reducing pre-existing taxes using environmental tax revenue; the tax interaction effect is the cost of exacerbating pre-existing distortions on goods with the new environmental tax.

The tax base effect is impacted in two ways by the features we include. First, the overall size of the tax base effect is moderated by the evasion rate – the effect is multiplied by $(1 - \epsilon_L)$. Second, the tax base effect includes only the change in formal labor supply $L - L_{SI}$. As labor moves from the informal to the formal sector (Bento et. al (2018)), this tax base effect becomes less negative.[12]

The third bracketed term is the tax evasion effect: the change in evasion and the change in real costs spent on tax evasion as a result of shifts in the tax system. Taxes on carbon (falling for example on gasoline or electricity) are relatively difficult to evade because they need to be assessed at only a relatively small number of large industrial facilities such as electric power plants and petroleum refineries (Liu (2013)). The policy change can therefore diminish the overall level of evasion. Variation in the rate of tax evasion will drive differences in welfare impacts.

The fourth bracketed term reflects the change in Ricardian rents as the carbon tax is changed. Decreases in profit here are matched by a reduction in the labor tax; the more heavily the changed tax system falls on Ricardian rents the lower the labor tax (and associated distortion) needs to be (Bento and Jacobsen (2007)).

[12] In some developing economies, including China, large corporations are the primary taxpayers and small companies on the margin of informality pay lower taxes. In this case, to realize the benefits of having informal labor migrate to the formal sector, tax cuts would need to be directed at the set of taxes and fees that these smaller firms also pay (Bento et. al 2018).

3 Simulation

We conduct a set of simulations to explore the magnitudes of the effects described above, showing how the factors combine and investigating their relative importance in stylized versions of the economies of the U.S., China, and India.

3.1 Numerical model

Households Utility is specified as a nested constant elasticity of substitution (CES) function:

$$U = \left(\alpha_{UG} C^{\frac{\sigma_U - 1}{\sigma_U}} + \alpha_{Ul} l^{\frac{\sigma_U - 1}{\sigma_U}}\right)^{\frac{\sigma_U}{\sigma_U - 1}}, \tag{18}$$

with the two consumption goods represented together in C:

$$C = \left(\alpha_{CG} G^{\frac{\sigma_C - 1}{\sigma_C}} + \alpha_{CS} S^{\frac{\sigma_C - 1}{\sigma_C}}\right)^{\frac{\sigma_C}{\sigma_C - 1}}. \tag{19}$$

As above l represents leisure and G and S manufactured goods and services respectively. The parameters σ_U and σ_C control the elasticities of substitution in utility; the parameters α_{UG} and α_{CG} control the baseline sizes of the sectors. Importantly, we assume for the purposes of simulation that there is no disutility from environmental damage, allowing us to focus the results of the simulation on the non-environmental "gross" welfare cost associated with specific reductions in energy use. The optimal corrective tax would be determined by pairing this model with estimates of an environmental benefit function.

Firms Functional forms for production in the intermediate and final sectors are given by:

$$E = \gamma_E \left(\alpha_{LE}^{1/\sigma_E} L_E^{\frac{\sigma_E - 1}{\sigma_E}} + \alpha_{FE}^{1/\sigma_E} F^{\frac{\sigma_E - 1}{\sigma_E}} \right)^{\frac{\sigma_E}{\sigma_E - 1}} \tag{20}$$

$$G = \gamma_G \left(\alpha_{LG}^{1/\sigma_G} L_G^{\frac{\sigma_G - 1}{\sigma_G}} + \alpha_{EG}^{1/\sigma_G} E_G^{\frac{\sigma_G - 1}{\sigma_G}} \right)^{\frac{\sigma_G}{\sigma_G - 1}} \tag{21}$$

$$S^F = \gamma_{SF} \left(L_{SF}\right)^{\theta_{LF}} \left(E_{SF}\right)^{\theta_{EF}} \tag{22}$$

$$S^I = \gamma_{SI} \left(L_{SI}\right)^{\theta_{LI}} \left(E_{SI}\right)^{\theta_{EI}} \left(D\right)^{\theta_{DI}} \tag{23}$$

$$D = L_D \tag{24}$$

Where the variables L_i and E_i represent the labor and energy used in production of good i. The parameters σ_E and σ_G control the elasticity of substitution between inputs; α_{LE}, α_{FE} , α_{LG} and α_{EG} determine baseline input shares. In the production of services, the parameters γ_{SF}, γ_{SI}, θ_{LF}, θ_{EF}, θ_{LI}, θ_{EI}, and θ_{DI} govern the productivity of inputs to S^F and S^I.

We make one key extension of the analytical model in Section 2 by allowing the presence of informal energy D. Informal energy sources, as discussed in Bento et al (2018), are outside the taxed economy and include agricultural residue, firewood, and burnt trash; these sources play a non-negligible role in the energy used in developing countries and have the potential to mitigate the informal sector effect (since carbon taxes would miss informal energy D, reducing cost to the informal sector. This extension also allows us to make more conservative estimates overall. Setting θ_{DI} to 0 in the simulation returns the structure to that of the analytical model.

Solution Equilibrium is a set of taxes and prices that achieves the carbon reduction goal, holds government revenue fixed, and clears markets for goods and labor. The model defines the pre-tax wage as the numeraire and uses a derivative-based search over carbon and labor taxes to meet the carbon emissions target and revenue neutrality constraints.

3.2 Calibration

Our calibration represents stylized versions of the three economies we study; the central case parameter values are shown in Table 1.

The set of parameters governing the informal sector follow Schneider (2005) which estimates the informal sector makes up 15.6% of the Chinese economy, 8.4% of the U.S. economy, and 25.6% of the Indian economy. We assume that the informal sector has the same overall energy intensity as the formal services sector.

Ricardian rents are calibrated to fossil energy extraction rents in each economy. The World Bank (2011) estimates total resource rents for a broad panel of countries. These rents are calculated by multiplying unit resource rents with the volume of each resource produced, where unit resource rents are simply the difference between the price of a resource and its cost. We sum the resource rents for oil and natural gas in each country.[13] Between 1995 and 2008, these were 2.6% of Chinese GDP, 0.9% of U.S. GDP, and 1.7% of Indian GDP.

Next we obtain the resource taxes collected in China from the China Tax Yearbook, an annual publication of the Chinese government. Between 1996 and 2005, the years for which we have data, the resource taxes collected were 3.1% of total resource rents. We obtained data on resource taxes collected in the U.S. from the Office of Natural

[13]Resource rents on coal are also available for these countries; resource rents on coal comprise about 15% of total rents in the U.S. and more than 50% of rents in both China and India. To be conservative, we chose not to include coal in our definition of the fixed factor because physical production limits on coal do not seem as applicable here as they are for oil and natural gas. Coal production also appears be limited by environmental regulation, rather than scarcity. Simulations including coal in the measurement of the fixed factor increase the magnitude of the effects relative to those in the tables below.

Table 1: Simulation Model Parameters

	China	U.S.	India
Composition of economy			
Formal services (energy intensity)	53% (3.0%)	78% (2.6%)	74% (6.6%)
Industry (energy intensity)	47% (16.4%)	22% (8.2%)	26% (24.0%)
Demand elasticities and base tax rates			
σ_U	0.9	0.9	0.9
σ_C	1.01	1.01	1.01
τ_E	0	0	0
τ_L	23.9%	41.6%	27.2%
Informal sector			
Fraction of economy	15.6%	8.4%	25.6%
Energy intensity	3.0%	2.6%	6.6%
Informal energy intensity	1.0%	0.03%	2.6%
Tax evasion			
Labor tax evasion rate	15.3%	9.3%	14.6%
Carbon tax evasion rate	7.6%	4.6%	7.3%
Cost of evasion (as percent of taxes evaded)	10%	10%	10%
Ricardian rents			
Resource rents, share of GDP	2.6%	0.9%	1.7%
Initial resource tax	3.1%	7.5%	6.4%

Resources Revenue, the agency tasked with monitoring and collecting taxes from natural resources. Between 2003 and 2008, the years for which data were available from both this source and the World Bank database, the taxes were 7.5% of resource rents. Indian oil and natural gas extraction revenue was obtained from the Indian Ministry of Petroleum and Gas, who publish their data online at the Open Government Data Platform. Between 2004 and 2008, taxes averaged 6.4% of total resource rents.

We calibrate tax evasion in each economy following Liu (2013), using self-employment rates as a proxy. This method is a conservative estimate of tax evasion, since the higher tax evasion rates of the self-employed are just one mechanism by which taxes are evaded. Using this method, we estimate the evasion rate in China to be 26.7% and the evasion rate in India to be 32.0%. Because this measure of tax evasion overlaps with the measure of the informal economy above, we assume that the entire informal economy pays no tax and that the rest of the economy evades at a lower, uniform rate. After removing the informal sector, we find a tax evasion rate in the formal sector of 15.3%. Similar to Liu (2013), we assume that the real cost of tax evasion is 10% of taxes evaded. We calibrate our value for the US economy using the same method, with overall evasion set to 16.3% (Slemrod 2007).

The energy intensities of each production sector are defined using the global GAINS model and aggregate data on GDP by sector from the 2011 CIA "World Factbook."[14] Energy intensity (in value terms) for services in China is 3.0%, and the energy intensity for industry is 16.4%. We calculate that the intensity of informal energy use is 1.0%. The industrial sector makes up 46.8% of China's economy, leaving 53.2% for the combined agricultural and industrial sectors. Combined, this implies that the baseline size of the energy sector as a whole is 9.3% of the economy. We follow the same process for

[14]See Bento et al. (2018). The GAINS model is a comprehensive database of local air pollutants and fuel sources including both formal and informal sources.

the U.S. yielding an energy intensity of 2.6% in services and 8.2% in industry. Informal energy use in the US is very small by comparison, 0.03%. In India, energy intensity is 6.6% in services and 26.3% in industry. Informal energy intensity is the highest in India at 2.6%, reflecting the widespread use of informal fuels in India.

We calibrate the preexisting tax rates in the economy to 29.3% of GDP in China, 38.9% of GDP in the US, and 27.0% of GDP in India, reflecting the level of government expenditures as a percentage of GDP.[15] The lower pre-existing tax rates in China and India make our estimates conservative in the sense that it works against finding a double dividend for these countries. Finally, the elasticities of substitution in utility are set to be $\sigma_U = 0.9$ and $\sigma_C = 1.01$, implying close to average substitution (Bento and Jacobsen (2007)). The sensitivity analysis in Section 3.4 explores the robustness of our findings to alternative parameter values along each of the dimensions above.

3.3 Results

We first show how each of the three factors enters individually and then present the combined effects.

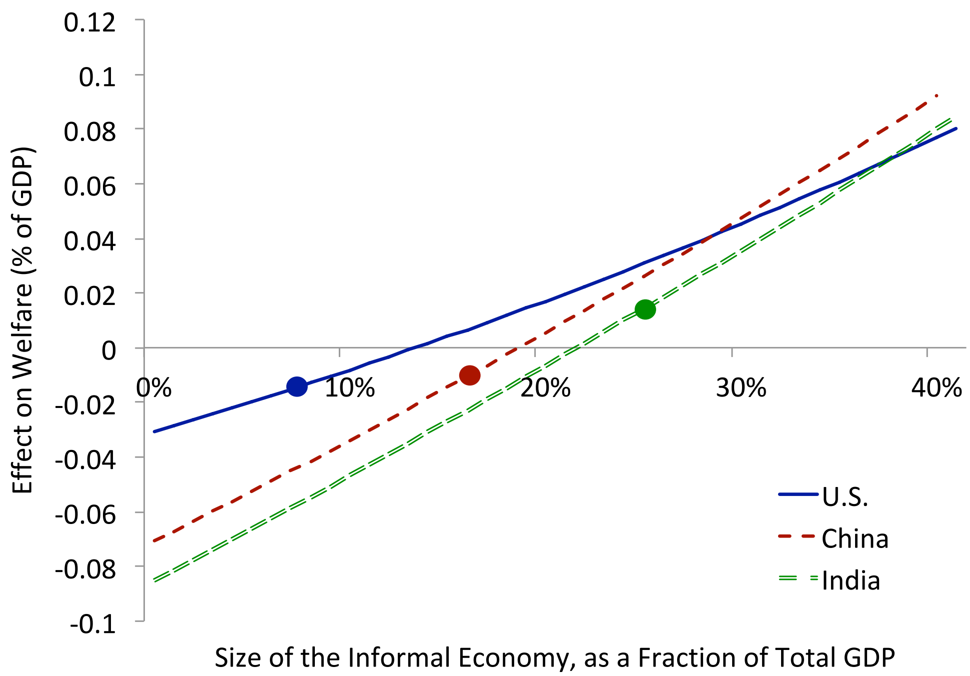
3.3.1 The Informal Economy

The influence of the informal economy in our model is isolated by setting fixed factor rents and formal sector tax evasion to zero. Figure 1 displays gross welfare costs of policy for a fixed emissions reduction of 10%, varying the size of the informal sector on the horizontal axis.

The y-intercepts of the two lines represent the baseline cost of the tax reform to reduce emissions by 10% when none of the three factors are considered. In keeping

[15] Heritage Foundation (2016).

Figure 1: The Effect of an Informal Economy on the Gross Cost of Carbon Taxes



with conventional wisdom, the cost of a revenue neutral carbon tax to China and India is more than twice as large as the cost in the U.S., reflecting the higher Chinese and Indian energy intensities.

The slopes of these lines reflect the reduction in cost of the policy reform as the informal sector grows in importance. Since movement from the informal sector to the formal one operates by elasticities, a larger informal sector induces a greater expansion of the formal sector. The U.S., with the smallest informal sector, has the least steep slope. China and India have much larger informal economies and hence steeper slopes so movements in informal labor can help cut the cost of the carbon tax policy much more.

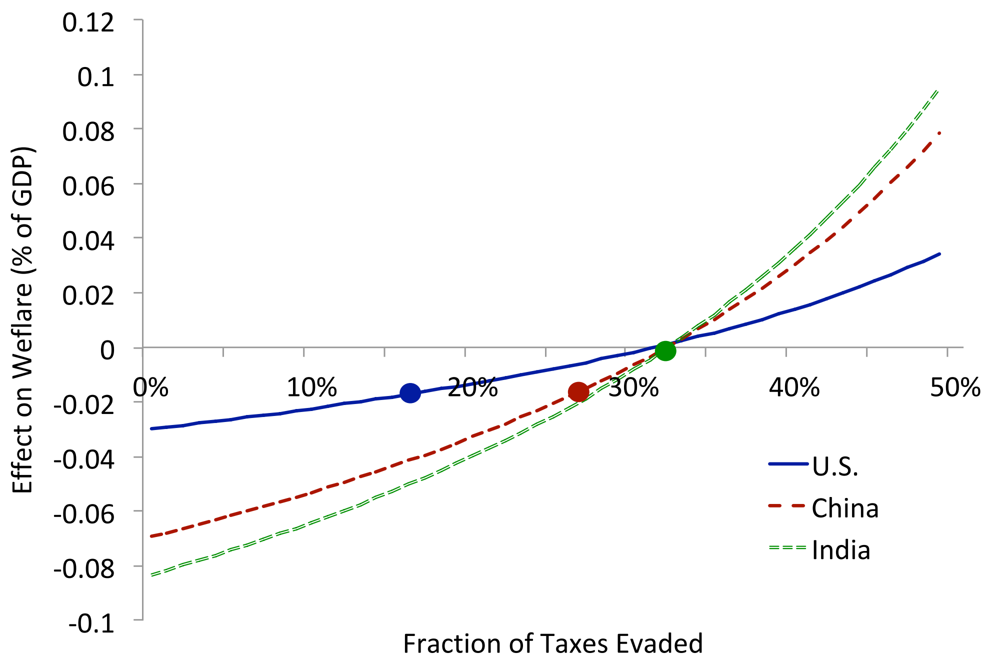
The highlighted point on each of the lines corresponds to the central case empirical estimate of the size of the informal economy in each country. The large (relative to the U.S.) informal economy in China cuts the cost in China much more than it does in the U.S., though we see that this effect alone is not enough to reverse the cost ranking: the effect of the informal sector in China roughly cancels out China's greater carbon intensity, making welfare costs in China and the U.S. quite similar. In constrast, India's (much) larger informal economy is enough by itself to make the welfare cost of shifting to a carbon tax negative. India goes from having the largest economic drag associated with a carbon tax (in the baseline where none of the three countries have an informal economy) to being the cheapest place to introduce a carbon tax. We note that other major carbon emitters with particularly large informal economies are Brazil, Mexico, and Russia.

3.3.2 Tax Evasion

The effect of the presence of costly tax evasion (by itself) is shown in Figure 2 and follows the same pattern as above. The mechanism comes via the fact that India's polluting sector is the largest (as a fraction of GDP) meaning that relatively more carbon tax revenue (and so larger cuts in pre-existing distortionary taxes) are possible for the same 10% reduction in emissions. Since spending on tax evasion is a function of pre-existing distortionary taxes, the greater tax cuts in India result in the largest savings with respect to tax evasion.

The difference between the countries is further sharpened when considering the point estimates of existing tax evasion (again shown via the highlighted points on each line). The large amount of tax evasion estimated to be present in India means that the carbon tax shift would have almost zero welfare cost; China and the U.S. experience smaller, but still quite important economically, reductions in gross welfare cost.

Figure 2: The Effect of Tax Evasion on the Gross Cost of Carbon Taxes



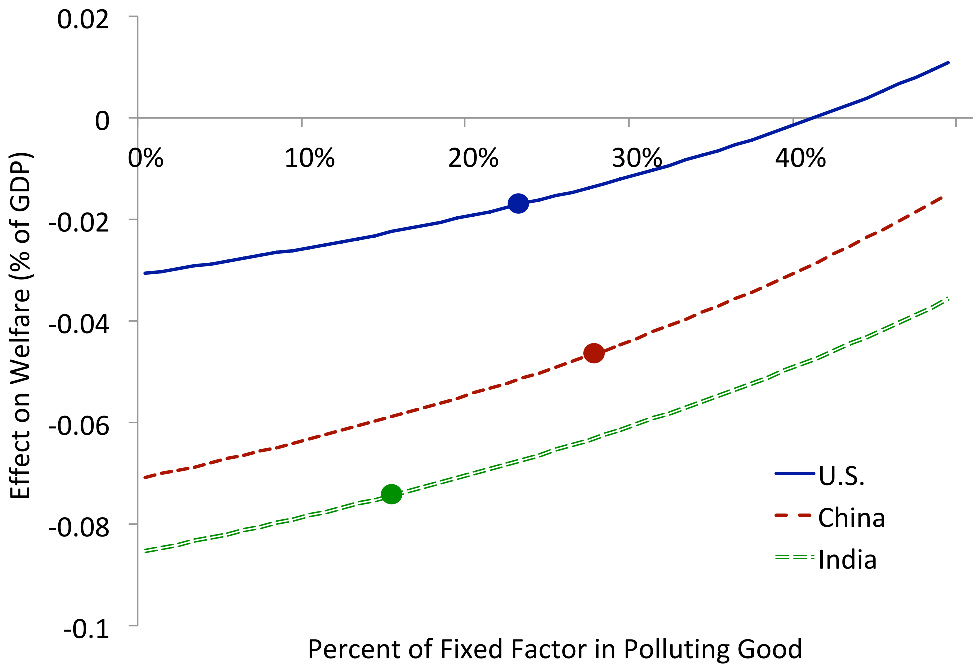
3.3.3 Ricardian Rents

We next consider the presence (again in isolation) of a fixed factor in the production of fossil energy. The results appear in figure 3.

By construction, the intercepts along the vertical axis reflect the same baseline as in the figures above. The slopes now represent the effect of introducing a fixed factor in energy production. The cost savings stem from the fact that a carbon tax acts as a surrogate tax on Ricardian rents that otherwise escape full taxation. When resource rents are a larger fraction of the economy this effect becomes more important. In our calibration, the rent effect results in roughly parallel slopes for each country.

The highlighted points show our central estimate of the size of the oil and natural gas production sectors in each country. Like the effects of informality and evasion, the presence of Ricardian rents reduces gross costs of carbon taxation importantly in each of the three countries. Unlike informality and evasion, the relative effect is similar in

Figure 3: The Effect of Ricardian Rents on the Gross Cost of Carbon Taxes



the three countries.

3.3.4 Combined Results

Our central simulation results bring together all three of the effects above. Table 2 displays key mechanisms and gross economic costs of carbon taxes that achieve a fixed 10% cut in carbon emissions in the three countries and using our central case parameters (Table 1). Cutting carbon emissions by 10% requires a carbon tax that raises the price of fossil energy by about 22% in China, 20% in the U.S., and 19% in India. The size of the informal sector shrinks more in China and India than in the U.S., reflecting the greater starting sizes of the informal sector in these countries. Ricardian rents are reduced by about 15% in China and 13% in the U.S. and India. The real cost of tax evasion declines in each country, with steeper declines in China and India. The Hicksian equivalent variation for this tax change is positive in all three

Table 2: Carbon Taxes to achieve a 10% Cut in Emissions: Key Mechanisms and Gross Costs

	China	U.S.	India
Size of carbon emissions reduction	10%	10%	10%
Carbon tax rate (initial rate)	0.22 (0.00)	0.20 (0.00)	0.19 (0.00)
Labor tax rate (initial rate)	0.27 (0.29)	0.38 (0.39)	0.25 (0.27)
Informal sector			
Change in formal labor (initial size)	0.42 (98.3)	0.11 (99.7)	0.41 (100.1)
Change in informal labor (initial size)	-0.17 (7.4)	-0.04 (4.3)	-0.21 (11.1)
Ricardian rents			
Change in rents (initial size)	-0.46 (3.12)	-0.14 (1.08)	-0.26 (1.96)
Tax evasion			
Change in labor tax evasion (initial rate)	-0.1% (15.3%)	-0.02% (9.3%)	-0.1% (14.6%)
Change in carbon tax evasion (initial rate)	7.5% (0%)	4.3% (0%)	7.0% (0%)
Change in evasion expenditure (initial expenditure)	-0.03 (0.5)	-0.01 (0.4)	-0.29 (0.4)
Equivalent variation as percentage of GDP	0.047%	0.011%	0.036%

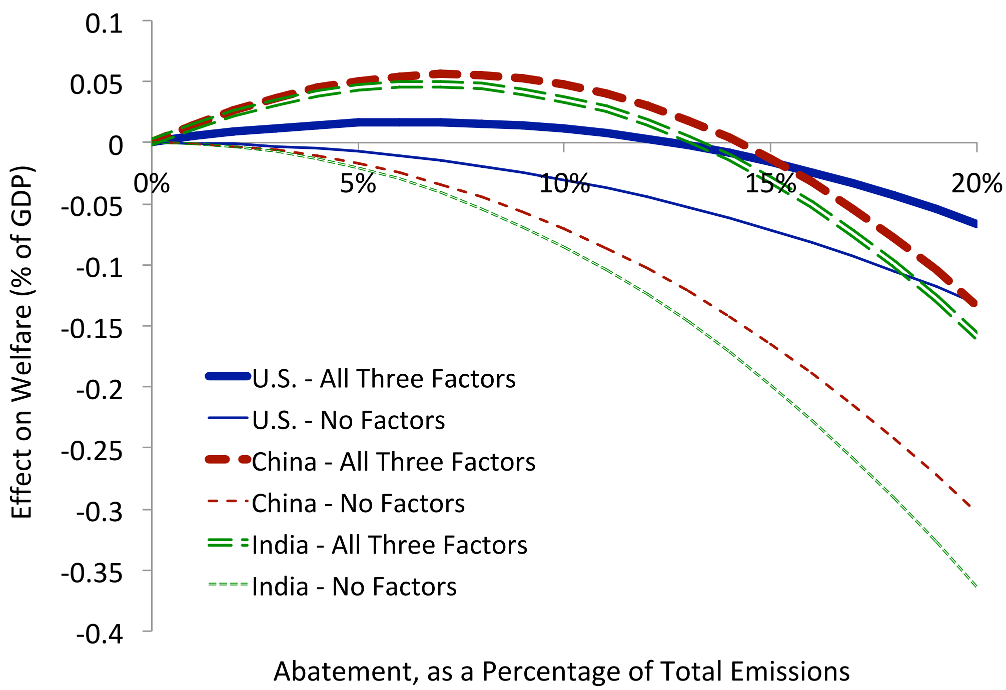
countries indicating that gross welfare gains are possible from a shift of revenue-raising instruments toward a carbon tax, even without considering environmental benefits.

Baseline Cost Without Informality, Fixed Factors, or Evasion

We next consider the way costs change over a range of targeted emissions reductions, no longer fixing them at 10%. Figure 4 illustrates our results with the horizontal axis varying the degree of emissions abatement between zero and 20%.

The thin lines for each country represent the cost of emissions reductions before considering informality, fixed factors, and evasion. These baseline costs of reducing emissions are positive throughout and exponentially increasing in abatement. They are more than twice as large in China and India as in the U.S., reflecting the greater energy intensities. The three thin lines in Figure 4 reproduce the common intuition that shifting to a carbon tax would be more painful for energy-intense developing countries than it would be for the U.S.

Figure 4: Effect of All Factors Combined on the Gross Cost of Carbon Taxes



Full Model

The thick lines represent equivalent variation when all three factors (the informal economy, costly tax evasion, and Ricardian rents) have been introduced together. For the U.S., the thick line lies everywhere above the thin line (representing baseline cost) and, for emissions reductions up to 13%, a gross welfare benefit (not counting environmental benefit) from a shift to a carbon tax is realized. This suggests that, even in the U.S.

economy where pre-existing taxes fall on a relatively broad base, a substantial carbon tax can be justified even without considering environmental gains. Factoring in the importance of environmental benefits further strengthens the case.

Turning to China, the thick red line (again, from the full model with all factors considered) again lies above the thinner baseline for all abatement targets in the plot. The combination of effects in China mean that emissions reductions up to 14% can be achieved with negative gross costs, and economic welfare is optimized with a reduction in emissions of 8% if we do not consider environmental benefits.

Finally, in India, the thick green line reflects negative gross cost for abatement targets up to 13%. Economic welfare excluding environmental benefits is optimized when emissions are reduced 7%.

The improvement in gross costs is much more important for China and India than it is for the U.S.: This reflects the relative inefficiency of existing revenue-raising taxes in China and India, leaving much greater room for welfare gain when some of the revenue is instead gathered using a carbon tax.

For much higher carbon tax rates, exceeding 100% the baseline price of fossil energy, we find the cost of abatement becomes larger when applying the full model. This comes from the way Ricardian rents enter: the presence of rents reduces costs initially (through the mechanism we study above) but for very high tax rates the revenue effect fades and emissions are persistent (a form of the "green paradox" where the presence of rents undercuts policy efforts). The inclusion of a renewable energy sector (e.g., solar, wind) with falling cost over time would introduce a different, likely much lower cost, dynamic and would important in developing a model aimed at studying cases with very high tax rates. When we consider the other two factors (tax evasion and the informal sector) without the rents model, the cost gains identified persist even as tax rates approach infinity (e.g. 100% abatement).

3.4 Sensitivity Analysis

Several alternative models and parameterizations that highlight the way each of the three factor enters in these economies are considered in a sensitivity analysis. The results appear in Table 3 with values displaying the gross welfare costs (excluding environmental benefits as before) as a fraction of the baseline. Each number in the table represents a separate simulation where emissions are cut 10% and positive values indicate cases with gross welfare gains.

In each row, we vary the way features of the model are included and consider two possible levels for the pre-existing factor tax burden in each country. The "high" cases refer to pre-existing tax burdens of 29%, 39%, and 27% in China, the U.S., and India respectively. These are drawn from long-run government expenditures and form the basis for the central estimates above. The "low" columns refer to pre-existing tax rates of 19% in China, 25% in the U.S., and 17% in India. These refer to the current tax burden as a percentage of GDP, which is lower than government expenditures in all three cases (Heritage Foundation 2016). These lower rates produces smaller gains in welfare since the key mechanism at work involves recycling revenue against pre-existing taxes.

The first three rows explore cases where each factor is added in isolation. The presence of an informal sector has the greatest impact on welfare, followed by tax evasion.

In the second group of cases, we include two factors at a time to see how omitting a given factor impacts our analysis. The informal economy has the largest impact on our results and omitting tax evasion has the least impact on the magnitudes of our results. This result follows from our assumption that the informal economy and tax evasion do not overlap (in the experiment, we effectively remove the entire informal economy from sectors that can evade taxes).

Table 3: Sensitivity Analysis

	China		U.S.		India	
Pre-existing labor tax	Low	High	Low	High	Low	High
No factors	-6.47	-6.91	-2.72	-3.07	-7.76	-8.52
Simulations isolating a single factor						
Informal economy alone	-3.30	-2.15	-1.68	-1.21	-3.41	-0.68
Ricardian rents alone	-5.82	-4.94	-2.24	-1.74	-7.67	-7.41
Tax evasion alone	-4.50	-4.49	-2.21	-2.34	-5.60	-5.61
Simulations combining two factors						
Ricardian rents and tax evasion	-3.48	-2.19	-1.70	-1.03	-5.30	-4.31
Informal economy and tax evasion	-1.74	-0.39	-1.25	-0.51	-1.85	1.07
Informal economy and Ricardian rents	-1.51	1.72	-0.91	1.11	-2.64	1.94
Alternative parameterizations						
Central estimate	0.21	3.45	-0.48	1.57	-1.00	3.58
Low informal economy	-0.49	2.36	-0.71	1.10	-1.77	2.07
High informal economy	5.77	12.30	1.33	5.41	5.29	16.62
Low tax evasion	-1.05	2.17	-0.15	1.95	-1.73	3.88
High tax evasion	1.92	5.29	-0.70	1.34	1.39	7.11
Low Ricardian rents	-0.81	1.42	-0.77	0.78	-1.01	3.53
High Ricardian rents	1.47	6.02	-0.13	2.56	0.10	6.95

Notes: Each value refers to the welfare cost of a revenue neutral policy that raises the carbon tax and cuts the labor tax, targeting an emissions reduction of 10%. The values are expressed in hundredths of a percentage point of GDP, with negative values indicating welfare losses, and positive values indicating welfare gains.

In the third set of cases, all three factors are included but now we alter input parameters to the model. First, low and high parameterizations of the informal economy are examined by modifying the slope parameter θ_L (set to 0.4 in the central case) to values of 0.33 and 0.67. For China, we look at a low and high importance of Ricardian rents by modifying the fraction of Ricardian rents as a share of the energy sector (0.28 in the central case) to 0.15 and 0.4. In the parallel simulations for the U.S. (0.22 in the central case) and India (0.22) we consider values of 0.15 and 0.3. Finally, low and high values for tax evasion in China (15% in the central case) and India (15%) of 5% and 25%, and low and high values in the U.S. (9% in the central case) of 5% and 15% are examined.

To summarize our results, we find that implementation of a carbon tax is always less costly than would be assumed if the three factors are not taken into account. We also find negative gross costs for many plausible combinations of parameters, implying economic benefits of a carbon tax even before considering the environmental benefits.

3.5 Additional Factors

While we consider only three factors that affect the cost of a carbon tax, there are other factors outside the scope of our model that can influence the properties of a carbon tax. Some of these, for example interactions between trade and carbon policy, may be more important in industrializing economies. Policy provisions like border tax adjustments (in the event of a unilateral carbon tax) have the potential to offset trade-related concerns, though are beyond the scope of what we do here.

Another key factor is worker productivity, now known to be reduced by air pollution (see Graff Zivin and Neidell (2012)). Potential improvements in productivity are likely to be especially large in developing countries due to the higher starting levels of air pollution and greater fraction of the population employed in manually intensive work.

This could lead to greater productively gains in developing economies than in the U.S. for an equivalent reduction in fossil fuel use. Further, the amount of local air pollution created per unit of fossil fuel use is also much larger in China and India than in the U.S. (IMF (2014)), making each unit of reduction more important in terms of local air pollution benefits.

Another important consideration is tax-favored consumption, as documented in Parry and Bento (2000). They point out that modern tax systems typically contain legislated favoritism in consumption, such as mortgage-financed housing or medical expenses in the U.S. To the extent that revenues from a carbon tax are used to cut pre-existing taxes, the distortions caused by this favoritism will be decreased. Here there is less empirical evidence on differences across countries. However, to the extent tax systems in developing countries are less able to produce uniform taxation across consumption goods, the effect we identify could again be strengthened. Related, regressivity concerns in developed countries can reduce the optimal tax on energy consumed directly by households (which is most typically in the form of gasoline and electricity). This concern is less likely in developing economies (where these same taxes are often progressive) and could further increase the wedge in optimal carbon taxes between countries.

3.6 Environmental Benefits

We have so far focused exclusively on the cost side of policy.[16] Large benefits from mitigation of climate change (e.g. Interagency Working Group (2016)), and from the reduction of co-pollutants, are clearly documented. For example in the regulatory

[16]While we concentrate on a selection of direct environmental impacts in this section, Williams (2003) has shown that changes in pollution levels that improve worker health can also influence the labor-leisure tradeoff and therefore tax interactions. The The net impact of these changes on economic welfare are unclear without additional assumptions.

analysis leading to the 2015 Clean Power Plan the economic benefits associated with reducing adverse health consequences related to co-pollutants exceed the (also substantial) value of climate mitigation.[17] In developing economies these co-benefits may be even larger: the recent Lancet Commission on Pollution and Health (Landrigan et al. (2018)) estimates that over six million people a year in low and medium income countries are dying from air pollution, a number which exceeds those killed by HIV and malaria. More specific to our setting, Aunan et. al (2007) explore co-benefits in China and conclude that the cost of cuts to China's carbon emissions are largely offset by benefits to public health and agricultural yields. The World Bank (2007) estimates that the effects of air pollution on increased mortality amount to 1.2% of GDP in lost physical production alone and 3.8% of GDP in willingness to pay for reduced mortality risk.

A full analysis would combine the marginal costs we estimate with a set of benefits associated with reduction in emissions of carbon and local air pollutants. To the extent costs are lower in developing economies (as we show here) and benefits are higher (as suggested in the literature) the relative strength of the case for a carbon tax could tilt quite strongly toward the developing world.

4 Discussion

Our results suggest that carbon taxes can play an important role in the optimal tax system even if environmental damages are ignored. The possibility that implementing a carbon tax in China, India and the U.S. could simultaneously reduce carbon dioxide emissions and enhance economic welfare has the potential to radically alter the dynam-

[17] The co-benefits literature quantifies the impact of the indirect benefits of instruments targeting carbon, such as the reduction in closely related pollutants like SO_2 and NO_X.

ics of what is both optimal and possible in terms of a global climate agreement (Aldy and Stavins, 2007).

Climate change negotiations are often viewed as a form of the prisoner's dilemma, where even though potential benefits are very large a set of co-ordination failures prevents reform. Our results here suggest that the level of cooperation sustainable in a game theoretic sense becomes larger, since the individual costs of tax reform are lower or even negative, when fully considering features of the existing tax system.

Our results are based on the presence of well-known distortions that make current systems of taxation less efficient and carbon-based taxes more efficient. The results we show depend critically on the details of how the carbon tax revenue is used (for example, lump sum rebates of revenue would leave the existing tax system in place and not take advantage of available efficiency gains). We also find that the results are strongest for moderate initial emissions reduction targets; extensions to the model would be required to consider longer-run, deeper cuts in emissions.

Intuitively, deeper cuts in emissions over time can remain consistent with the double dividend result here provided that R&D investments drive down the primary cost of carbon reductions fast enough over time. In the simplest case, the magnitude of the carbon dioxide reductions that can be achieved over time at no net cost increases at the same rate as the technical cost of achieving that reduction declines.[18] Related, Acemoglu et al. (2012, 2016) point out that the specific nature of R&D investments (e.g., improving the efficiency of existing fossil fuel-based energy consumption versus clean energy technologies) can have substantial influence on the nature of the medium run paths open to an economy to achieve a carbon target, and that their interaction with any carbon tax needs to be carefully considered. Our results here would argue

[18] A more subtle countervailing effect has to do with the carbon tax base: as an economy becomes very clean the revenue available from a carbon tax shrinks, and along with it the potential value of recycling that revenue to improve the tax system.

that, to the extent baseline energy efficiency is lower in China (Yao et al. 2012) or India, R&D advances that would allow leapfrogging to low cost low carbon intensity technology could have a proportionally greater impact on growth in these countries than in the U.S.

Induced technological change (Goulder and Mathai (2000)) may also contribute to a lower cost of carbon tax reform than would be assumed from a simple baseline. This is documented in Popp (2002) where higher energy prices lead to increases in the number of energy efficiency patents. Liu and Yamagami (2018) analyze the effects of induced technological change in a similar model of environmental policy, finding that this effect does leas to reductions in the estimated cost of carbon taxes, but by smaller amounts than the three factors studied in the present paper.

Finally, even though a structural shift toward a carbon tax increases aggregate welfare in our model, heterogeneity will create both winners and losers in practice. To the extent the value (and scale relative to GDP) of carbon tax revenue is greater in China and India they may have more flexibility than the U.S. to smooth impacts across industries and individuals. These countries also have proportionately larger environmental benefits in the form of health and environmental co-benefits that could shrink the fraction of the population experiencing a net loss.

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Appendix: Derivation of Welfare Formulas

Combining equations (10) and (11) allows us to restate the household optimization problem as:

$$W = u\left(G, S, \overline{L} - L\right) - \phi\left(E\right) - \lambda\left[p_G G + p_S S - L - H - \pi_{FF} - \pi_{SN}\right] \qquad (25)$$

Totally differentiating with respect to τ_E and plugging in the envelope conditions for utility yields:

$$\frac{1}{\lambda}\frac{dW}{d\tau_E} = -\frac{1}{\lambda}\phi'\left(E\right) - \frac{dp_G}{d\tau_E}G - \frac{dp_{SF}}{d\tau_E}S + \frac{d\pi_{FF}}{d\tau_E} + \frac{d\pi_{SN}}{d\tau_E} \qquad (26)$$

If we take the derivative of equation (11), the household budget constraint, with respect to τ_E while setting budget neutrality $\frac{dH}{d\tau_E} = 0$, we find that:

$$-\frac{dp_G}{d\tau_E}G - \frac{dp_S}{d\tau_E}S + \frac{d\pi_{FF}}{d\tau_E} + \frac{d\pi_{SN}}{d\tau_E} = p_G\frac{dG}{d\tau_E} + p_S\frac{dS}{d\tau_E} - \frac{dL}{d\tau_E}$$

Substituting this result into equation (26) yields:

$$\frac{1}{\lambda}\frac{dW}{d\tau_E} = -\frac{1}{\lambda}\phi'\left(E\right) + p_G\frac{dG}{d\tau_E} + p_S\frac{dS}{d\tau_E} - \frac{dL}{d\tau_E} \qquad (27)$$

For any given tax change, firms will take tax rates as given and optimize inputs, outputs, and tax evasion. Since $p_L = 1 + \left(1 - \epsilon_L\left(\tau_L\right)\right)\tau_L + \gamma_L\left(\tau_L\right)$, when we set the derivatives of equations (12), (13), (14), and (15) equal to zero we obtain:

$$p_G \frac{dG}{d\tau_E} = (1 + (1 - \epsilon_L) \tau_L + \gamma_L) \frac{dL_G}{d\tau_E} - \left(\frac{\partial \epsilon_L}{\partial \tau_L} \frac{d\tau_L}{d\tau_E} \right) \tau_L L_G + \left(\frac{\partial \gamma_L}{\partial \tau_L} \frac{d\tau_L}{d\tau_E} \right) L_G + p_E \frac{dE_G}{d\tau_E}$$

$$p_S \frac{dS^F}{d\tau_E} = (1 + (1 - \epsilon_L) \tau_L + \gamma_L) \frac{dL_{SF}}{d\tau_E} - \left(\frac{\partial \epsilon_L}{\partial \tau_L} \frac{d\tau_L}{d\tau_E} \right) \tau_L L_{SF} + \left(\frac{\partial \gamma_L}{\partial \tau_L} \frac{d\tau_L}{d\tau_E} \right) L_{SF} + p_E \frac{dE_{SF}}{d\tau_E}$$

$$p_S \frac{dS^I}{d\tau_E} = \frac{dL_{SI}}{d\tau_E} + \left(\frac{\partial \epsilon_L}{\partial \tau_L} \frac{d\tau_L}{d\tau_E} \right) \tau_L L_E + p_E \frac{dE_{SI}}{d\tau_E}$$

$$\begin{aligned} p_E \frac{dE}{d\tau_E} &= ((1 - \epsilon_E) \tau_E + \gamma_E) \frac{dE}{d\tau_E} - \frac{d\epsilon_E}{d\tau_E} \tau_E E + \frac{d\gamma_E}{d\tau_E} E \\ &\quad + (1 + (1 - \epsilon_L) \tau_L + \gamma_L) \frac{dL_E}{d\tau_E} - \frac{d\epsilon_L}{d\tau_E} \tau_L L_E + \left(\frac{\partial \gamma_L}{\partial \tau_L} \frac{d\tau_L}{d\tau_E} \right) L_E - \frac{d\pi_{FF}}{d\tau_E} \end{aligned}$$

Since $S = S^F + S^I$, we can plug these derivatives into equation (27) to yield:

$$\begin{aligned} \frac{1}{\lambda} \frac{dW}{d\tau_E} &= -\frac{1}{\lambda} \phi' (E) \frac{dL}{d\tau_E} + ((1 - \epsilon_E) \tau_E + \gamma_E) \frac{d_E}{d\tau_E} + (1 - \epsilon_L) \tau_L \left(\frac{dL_G}{d\tau_E} + \frac{dL_{SF}}{d\tau_E} + \frac{dL_E}{d\tau_E} \right) \\ &- \frac{d\epsilon_L}{d\tau_E} \tau_L (L_G + L_{SF} + L_E) - \frac{d\epsilon_E}{d\tau_E} \tau_E E + \frac{d\gamma_E}{d\tau_E} E + \left(\frac{\partial \gamma_L}{\partial \tau_L} \frac{d\tau_L}{d\tau_E} \right) (L_G + L_{SF} + L_E) - \frac{d\pi_{FF}}{d\tau_E} \end{aligned} \tag{28}$$

Since $L = L_G + L_{SF} + L_{SI} + L_E$, we can re-arrange to yield equation (17) in the main text.