Comparing the Cost of a Carbon Tax in China and the United States

Richard T. Carson[a], Mark R. Jacobsen[b], and Antung A. Liu[c]

September 2014

Abstract

Conventional wisdom holds that, without considering environmental benefits, a carbon tax would reduce welfare and that these costs will be higher in developing countries. We find strong evidence for the opposite conclusions. We show how three factors explored in the prior literature can combine to reduce the welfare cost of a carbon tax, and that these effects are particularly strong in developing economies. Incorporating informal production, untaxed Ricardian rents, and tax evasion, we conduct a series of numerical simulations for China and the U.S. We find that the costs of carbon tax policy in China are lower than those in the U.S. for emissions reductions up to 12%. Further, we see that overall efficiency costs are negative in both countries for a significant range of abatement targets: raising government revenue using a carbon tax is in fact cheaper than existing tax policy. We believe our results extend to the tax systems in many developing economies.

[a]Department of Economics, University of California, San Diego. Email: rcarson@ucsd.edu.

[b]Department of Economics, University of California, San Diego. Email: m3jacobsen@ucsd.edu.

[c]Cheung Kong Graduate School of Business and Resources for the Future. Email: antung@ckgsb.edu.cn and liu@rff.org.

1 Introduction

China and the United States are the two largest carbon-emitting countries in the world, currently responsible for more than 40% of the world's carbon emissions. China is not only the top emitter; it also has one of the highest growth rates and will account for half of the projected increase in emissions between 2010 and 2040.[1] As such, these two countries represent the most important contexts in which to study the effects of emissions-targeting policies on economic growth and welfare.

The prior literature has long held that instituting a carbon tax trades off better environmental quality against lower economic growth, even when the carbon tax revenue is recycled to cut pre-existing taxes. This result represents rejection of the once popular conjecture, known as the double dividend hypothesis, that it was possible to improve environmental quality through the use of carbon taxes while simultaneously increasing economic growth by decreasing taxes on desirable activity such as the supply of capital and labor. For example, in their summary of work in this literature Parry et al (2012) state: "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." A direct consequence of this finding is that the (second best) optimal environmental tax is below the level of marginal external damages.

We re-examine this conclusion by pointing out that most of the earlier findings[2] were developed under the implicit assumption of optimal tax systems with OECD economies in mind, where fewer and less prominent pre-existing tax distortions are present. In developing economies, tax systems are far from optimal. If the tax system

[1]Current and projected emissions from U.S. Energy Information Administration (2013).

[2]See for example 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).

into which the carbon tax is introduced is not optimal, the policy can be less costly to the extent to which carbon taxes counteract these pre-existing distortions.

We focus in this paper on three tax distortions that have been shown in the prior literature to play an important role. Each of these are more prominent in developing countries than in OECD countries. First, the informal sector comprises a much larger share of the economy in developing economies. Bento, Jacobsen and Liu (2014) show how carbon taxes tend to fall on goods that have poor substitutes in the informal sector. When the size of government is expanded using carbon tax revenue rather than taxes such as labor taxes, less tax base leakage into the informal sector occurs, improving the relative attractiveness of carbon taxes. Second, developing countries are typically more dependent on the extraction of fixed and exhaustible resources. Bento and Jacobsen (2007) show how the presence of Ricardian rents, which accrue to these resources, can lower the cost of reform when carbon taxes act as a surrogate tax on these rents. Third, developing countries typically have much higher tax evasion. Liu (2013) argues that taxes on carbon are much harder to evade than most other taxes and shows that the implementation of a carbon tax diminishes the incentives to evade and can result in large cuts to the cost of reform.[3]

We sequentially add these three features to the standard analytical model used to examine the optimality of a carbon tax and study how each feature enters. We then simulate the empirical relevance of these factors in China and the U.S. Not surprisingly, China has a larger informal sector and much more tax evasion than the United States. Its economy is also more heavily dependent on extractible resources than that of the United States.[4]

[3]The relatively small number of firms (e.g., oil refineries and power plants) that need to be monitored with respect to collecting a carbon tax form an important part of the increased difficulty of evasion. See Metcalf and Weisbach (2009) for further discussion of this issue.

[4]In addition, the effective initial tax rate in the U.S. is substantially larger. A higher initial tax rate reduces potential gains to welfare from carbon taxes: the effect in Bento and Jacobsen (2007)

We first show in our baseline case – without considering any of these three factors – that a carbon tax swap results in a negative welfare impact for both China and the United States over the entire range of emissions. Since China's economy has more heavy industry and its energy mix is more carbon-intensive, the negative impact for any given reduction in emissions is larger for China than it is for the United States. This is consistent with the stated beliefs of the leaders of many developing countries.

We next represent the role of resource rents, informal production, and tax evasion in the two countries using plausible values for key parameters taken from the literature. We show how each factor separately and cumulatively reduces the cost of environmental tax reform.

The simulations produce two key results. First, gross welfare cost - not accounting for environmental improvement - is negative for emissions cuts of 10% in the U.S. and China. In other words, the baseline cost of cutting carbon emissions in these two countries is more than fully offset by the importance of fossil fuel rents, informality, and evasion. Second, we find that the ranking of policy costs for China and the U.S. is reversed. In spite of China's greater energy intensity the cost of a carbon tax, expressed as a fraction of GDP, is actually lower in China than the U.S. for emissions reductions up to 12%. For larger emissions cuts we find that the expected wedge in costs between the two countries is greatly reduced.

Our results come with some important caveats. While we build on three established effects in the literature there are also numerous complexities in the tax codes of each country that could further influence the relative cost of a carbon tax; finely detailed models of each economy could study these issues, though may come at the cost of transparency. Further, there will be entities who would suffer substantial losses from

depends on the ability of carbon taxes to eliminate Ricardian rents which only accrue under incomplete taxation.

a carbon tax that will fight its implementation. Our results, however, suggest that finance ministry officials in China and likely other developing countries do not need to fear that they are sacrificing economic growth to get moderate reductions in carbon emissions. The potential for a carbon tax double dividend in many developing countries is likely to have implications for the structure of international negotiations over climate policy.

In addition, our analysis casts into question who the winners and losers of a coordinated emissions reduction might be. Developing countries, who tend to have higher confluences of the three factors analyzed here, would have relatively more to gain from reforming their tax systems towards carbon taxes. OECD countries, whose systems are closer to optimal, have comparatively lower incentives to make these reforms.

Section 2 of our paper lays out the analytical model used here and adds an informal economy, Ricardian rents, and tax evasion sequentially. Section 3 presents the numerical model we use to estimate the magnitudes of the effects, and shows how we calibrate our estimates. Section 4 discusses our results and concludes.

2 Analytical Model

Developing countries have tax systems that deviate sharply from the assumptions of the neoclassical, optimal tax model in several ways. Here we incorporate three of them into a formal analytical framework, drawing on the analytical models from the prior literature. Following Bento et al (2014), we allow for the presence of an informal sector. Following Bento and Jacobsen (2007), we incorporate a fixed factor in the production of fossil energy. Finally, following Liu (2013), we incorporate tax evasion. Because the model is meant to be illustrative, it is simpler than the numerical simulations in section 3.[5] We build from a standard optimal tax model commonly used to examine the cost of shifting the tax base toward a carbon-emitting fossil energy sector.[6]

2.1 Firms

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

2.1.1 Manufacturing and Services

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

Manufactured goods are produced using labor L_G and fossil energy E. Production is assumed constant returns to scale:

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

Firms that produce formal sector services S^M use only labor and again have constant returns to scale:[7]

$$S^M = L_{SM} \tag{2}$$

The Informal Economy The third type of firm produces informal services S^N. This sector again uses only labor. In contrast to the other sectors, we assume that marginal cost is increasing, resulting in an upward sloping supply curve. As the informal sector

[5] In simulation we allow energy to be used in each sector of the economy, rather than just the manufacturing sector. We also include informal energy.

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

[7] We relax this simplification in our numerical simulations by having services also consume energy. The key requirement for our results is only that services consume less energy than manufacturing; the simplification here is for ease of exposition and follows Bento et al. (2014).

scales up, it requires more infrastructure, becomes a greater target of government scrutiny, and generally becomes more difficult to hide.

We assume that informal sector production follows:

$$S^N = (L_N)^{\theta_L} \tag{3}$$

In this equation, L_N is the labor used in the informal sector and θ_L is a parameter between 0 and 1 which controls the slope of the marginal cost curve.

We combine the rising marginal cost curve with the assumption that formal sector services S^M and informal sector services S^N 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 then controls the degree to which informal production is important in an economy.[8]

2.1.2 Fossil Energy Firms

The final type of firm produces fossil energy, used only as an intermediate in the production of G. For simplicity each unit of energy E generates one unit of carbon, making taxes on energy or carbon equivalent. The production function $E(.)$ is constant returns to scale and requires two inputs:

$$E = E(L_E, F) \tag{4}$$

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

$$\pi_{SN} = \int_0^{MC^{-1}(p_{SN})} [p_{SN} - MC(L)]\, dL$$

The first input is labor L_E and the second is a fixed factor F, generating the rents explained in detail below.

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 We model the fixed factor in this setting as an immobile resource that is used intensively in the production of energy. In Bento and Jacobsen (2007), exhaustible resources such as oil and natural gas appear as examples.

While the production of other inputs is competitive, production of the fixed factor is not. This results in Ricardian rents accruing to the owners. An optimal tax system would fully tax away Ricardian rents since this form of tax revenue does not distort behavior. We assume that the current tax on extraction is τ_F and hold it fixed as environmental policy is introduced.

If p_E is the price of energy, $p_E E$ is the amount of revenue earned by energy producers. Owners of the fixed factor charge prices which make energy producers just indifferent to shutting down, so rents π_{FF} are given by the equation:

$$\pi_{FF} = p_E E - (1 + \tau_L) L_E - \tau_F F \tag{5}$$

2.2 The Government

The government collects three forms of taxes: labor taxes τ_L, energy or carbon taxes τ_E, and extraction taxes on the fixed factor τ_F. The collection of taxes is not complete, but instead suffers from a phenomenon pervasive in all modern tax systems: tax evasion.

Tax Evasion Tax $i\epsilon\{L, E\}$ may be evaded at rate ϵ_i. An evasion rate of 0 means that all taxes are completely paid; a 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:

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

We assume, without loss of generality, that the extraction tax τ_F is 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 is moderated by the amount of tax actually paid:

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

2.3 Households

There is one representative household which buys all goods and services, supplies all labor, and owns all firms.

Households gain utility from consuming the two final products, manufactured goods G and services S, and from consuming leisure (l). Services are a combination of formal services and informal services:

$$S = S^M + S^N \tag{8}$$

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 includes carbon and also local pollutants in the air and water. The disutility is given by $\phi(E)$ and assumed to be weakly convex.

We assume that $u(.)$, the utility function from non-environmental goods, is quasi-concave. The overall household utility function is then given by:

$$U = u\left(G, S, \overline{L} - L\right) - \phi(E) \tag{9}$$

There are four sources of income for households. The first is labor; the after-tax wage is normalized to 1. The second are lump-sum transfers from government. The third are profits from the household's ownership of the fixed factor F. The fourth are profits from ownership of informal firms. Together, the household budget constraint is:

$$p_G G + p_S S = L + H + \pi_{FF} + \pi_{SN} \tag{10}$$

2.4 Prices

Since the after-tax wage is normalized to 1, the cost of labor to firms is $1 + \tau_L$. The markets for energy, manufactured goods, and services are competitive and firms earn no profits in these areas.

The production cost of energy, $cost_E$, is determined by the sizes of the labor tax, the energy tax, and the price of the fixed factor. The final price of energy is this cost, plus the cost spent on evading the labor and energy taxes:

$$p_E = cost_E(\tau_L, \tau_E, \tau_F) + \gamma_E(\tau_E) + \gamma_L(\tau_L) \tag{11}$$

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

$$p_G = cost_G\left(\tau_L, \tau_E, \tau_F\right) + \frac{E}{G}\gamma_E\left(\tau_E\right) + \gamma_L\left(\tau_L\right) \tag{12}$$

Producers of formal sector services use only labor. They evade labor taxes at rate ϵ_L and must pay $\gamma_L\left(\tau_L\right)$ to do so. As a result, price is given by:

$$p_{SM} = 1 + \left(1 - \epsilon_L\right)\tau_L + \gamma_L\left(\tau_L\right) \tag{13}$$

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

$$p_{SN} = p_{SM} \tag{14}$$

2.5 Welfare Analysis

We derive the change in welfare coming from an increase in the fossil energy tax (equivalent to a carbon tax here) combined with a revenue-neutral reduction in the labor tax. This amounts to a tilt on the margin toward an energy 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 we decompose the welfare measure into the following components (a derivation appears in the appendix):

$$\frac{1}{\lambda}\frac{dW}{d\tau_E} = \left[\left(\frac{\phi'}{\lambda} - \left(1 - \epsilon_E\right)\tau_E\right)\left(-\frac{dE}{d\tau_E}\right)\right] + \left[\left(1 - \epsilon_L\right)\tau_L\frac{d\left(L - L_{SN}\right)}{d\tau_E}\right] - \left[\left(L - L_{SN}\right)\gamma_L^{'} - E\gamma_E^{'}\right] + \left[\frac{d\pi_{FF}}{d\tau_E}\right] \tag{15}$$

The first bracketed term balances the welfare gain from reduced pollution, $\phi^{'}$, against the primary cost of increased distortion in energy markets (where the primary cost is proportional to the pre-existing tax wedge on energy). If starting from a situation with no energy tax the primary costs go to zero on the margin, leaving only the gain from improved environmental quality in this first term. In developing economies, where pollution levels are typically higher than in OECD countries, we expect that these gains will be relatively more important.[9]

The second bracketed term is the tax base effect on labor, the primary factor of production. This includes both a "revenue recycling effect" and a "tax interaction effect." In our combined simulation, 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: note the effect is multiplied by $(1 - \epsilon_L)$. Second, the tax base effect includes only the change in formal labor supply $L - L_{SN}$, rather than the impact on all labor. If labor moves from the informal to the formal sector, as described in Bento et. al (2014), this tax base effect will become less negative. In our setting here, developing economies are likely to have a less negative tax base effect because they have larger informal sectors.[10]

The third bracketed term is the tax evasion effect: the change in real costs spent on tax evasion as a result of shifts in the tax system. As described in Liu (2013) taxes on energy (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. The policy change we study can therefore diminish the overall level of evasion in the system. Because tax evasion in

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

[10]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 2014).

developing countries tends to be higher to begin with, we also expect the tax evasion effect to be more important to welfare.

The fourth bracketed term reflects the change in Ricardian rents as the energy tax is increased. Decreases in profit here will be 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). Many developing countries are more dependent on the extraction of exhaustible fossil fuel than are OECD countries. This suggests that the resource rent factor may also play a greater role in developing countries.

We observe that each of the bracketed terms is likely to be more positive (or less negative) in developing countries than in industrialized ones, implying larger optimal carbon or energy taxes. We can also use this decomposition to consider cases that abstract from the environmental benefit (set $\phi'(E)$ to zero) and measure only the gross cost of policy. In this setting we observe that the potential welfare gains in the final three terms are not bounded to be smaller than the primary distortionary cost of policy in the first term. Gross costs could in fact be negative (this is again more likely in developing countries along the lines of the arguments above) which would imply gains from a carbon tax even absent environmental benefits.

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 Chinese and U.S. economies. We find that the combined effects are large enough to reverse conventional wisdom on the ranking of emissions policy cost in the U.S. and China. Our results are robust to a broad set of alternative parameterizations.

3.1 Numerical model

Households We now specify utility directly in a nested constant elasticity of substitution (CES) form:

$$U = \left(\alpha_{UG} C^{\frac{\sigma_U - 1}{\sigma_U}} + \alpha_{Ul} l^{\frac{\sigma_U - 1}{\sigma_U}}\right)^{\frac{\sigma_U}{\sigma_U - 1}} \tag{16}$$

$$C = \left(\alpha_{CG} G^{\frac{\sigma_C - 1}{\sigma_C}} + \alpha_{CS} S^{\frac{\sigma_C - 1}{\sigma_C}}\right)^{\frac{\sigma_C}{\sigma_C - 1}} \tag{17}$$

where l represents leisure and C an aggregate good including both manufactured goods and services. G represents the manufactured good and S services. 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. We abstract from the utility cost of environmental damages for these simulations and present results in terms of the welfare cost to achieve specific reductions in energy use. An optimal corrective tax could be determined by joining our model with estimates of the environmental benefit function.

Firms We make two important departures from the analytical model above in defining the structure of firms. These capture the presence of countervailing energy use in the informal sector and make our estimates of a possible double dividend more conservative. First, we allow for the use of energy (E) in services S^M and S^N. We now denote energy used in the manufacturing sector (G) as E_G, and energy used in the services sectors as E_{SM} and E_{SN}.

Our second departure is the presence of informal energy D. Informal energy sources, as discussed in Bento et al (2014), 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 also have the potential to mitigate the informal sector effect we study.

Production is then given as follows:

$$E = \gamma_E \left(\alpha_{LE}^{1/\sigma_E} L_E^{\frac{\sigma_E - 1}{\sigma_E}} + \alpha_{FE}^{1/\sigma_E} F^{\frac{\sigma_E - 1}{\sigma_E}} \right)^{\frac{\sigma_E}{\sigma_E - 1}} \tag{18}$$

$$G = \gamma_G \left(\alpha_{LG}^{1/\sigma_G} L_G^{\frac{\sigma_G - 1}{\sigma_G}} + \alpha_{EG}^{1/\sigma_G} E_G^{\frac{\sigma_G - 1}{\sigma_G}} \right)^{\frac{\sigma_G}{\sigma_G - 1}} \tag{19}$$

$$S^M = \gamma_{SM} \left(L_{SM} \right)^{\theta_{LM}} \left(E_{SM} \right)^{\theta_{EM}} \tag{20}$$

$$S^N = \gamma_{SN} \left(L_{SN} \right)^{\theta_{LN}} \left(E_{SN} \right)^{\theta_{EN}} \left(D \right)^{\theta_{EN}} \tag{21}$$

$$D = L_D \tag{22}$$

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_{SM}, γ_{SN}, θ_{LM}, θ_{EM}, θ_{LN}, θ_{EN}, and θ_{DN} govern the productivity of inputs to S_M and S_N.

Solution Equilibrium is a set of taxes and prices such that the carbon reduction goal is achieved, government revenue is held fixed, and the goods and labor markets clear. The model sets the pre-tax wage as the numeraire and uses a derivative-based search over energy and labor taxes to meet the carbon emissions target and revenue neutrality constraints.

Table 1: Simulation Model Parameters

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

3.2 Calibration

The baseline represents stylized versions of the Chinese and U.S. economies. Table 1 lists the central case parameter values we employ.

We first calibrate the parameters governing the informal sector. Following Schneider (2005), the informal sector makes up 15.6% of the Chinese economy and 8.4% of the U.S. economy. We assume that the informal sector has the same overall energy intensity of the formal services sector. The energy intensities of each sector and the size of the informal energy sector are calculated below.

We next calibrate rents from the relevant fixed factors (here, fossil energy) in each economy. The World Bank (2011) calculated 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 China and the U.S. Between 1995 and 2008, these were 2.6% of Chinese GDP, and 0.9% of U.S. 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 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.

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%. Because this measure of tax evasion overlaps with the measure of the shadow economy above, we assume that the entire shadow 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."[11] 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 the United States 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, at only 0.03%.

We calibrate the preexisting tax rates in the economy to 23.9% of GDP in China and 41.6% of GDP in the US, reflecting the level of government expenditures as a percentage of GDP.[12] The level of taxes in the U.S. is very similar to the 40% levels employed in the previous literature (for example Bento and Jacobsen [2007] and Liu [2013]). The lower pre-existing tax rate in China makes our estimates conservative in the sense that it works against the existence of a double dividend in China. Finally, we set the elasticities of substitution in utility such that $\sigma_U = 0.9$ and $\sigma_C = 1.01$, implying close to average substitution and again similar to prior work (Bento and Jacobsen [2007]). The sensitivity analysis in Section 3.4 explores the robustness of our findings to alternative parameter values.

3.3 Results

We first show how each of the three factors enters individually and then present the combined effects for the U.S. and Chinese tax systems.

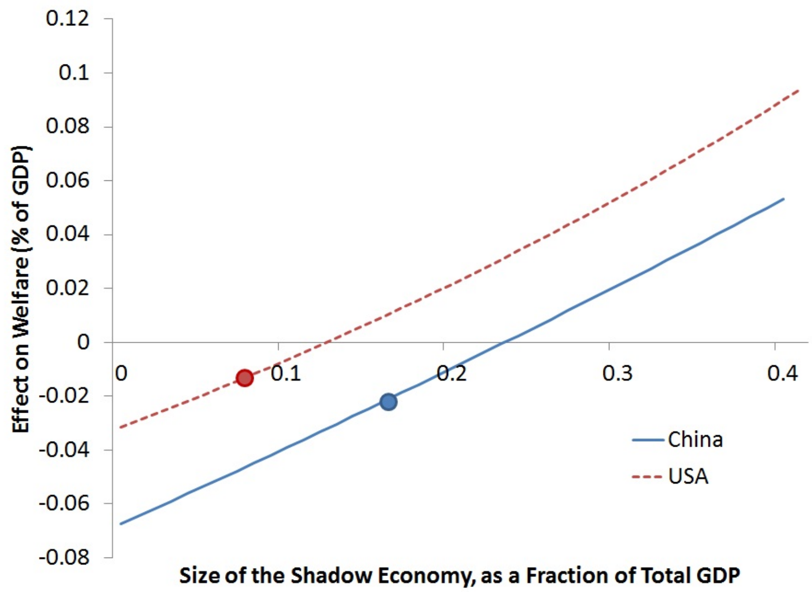
[11] See Bento et al (2014). The GAINS model is a comprehensive database of local air pollutants and fuel sources including both formal and informal sources.

[12] Heritage Foundation (2014).

3.3.1 The Informal Economy

We isolate the influence of the informal economy in our model by setting the size of the fixed factor and the amount of tax evasion to zero. Figure 1 displays the gross welfare costs of policy for a fixed emissions reduction of 10%, varying the size of the informal sector on the horizontal axis. Each point represents the results of a separate simulation.

Figure 1: The Effect of the Shadow Economy on the Cost of Carbon Emissions Cuts



First consider the y-intercepts of the two lines, representing the baseline cost of the tax reform to reduce emissions by 10% when none of the three factors are considered. The cost in China is 0.067% of GDP and is more than twice as large as the cost of reform in the U.S. The policy is more expensive in China mainly due to the larger size of the industrial sector and more energy-intensive production mix.

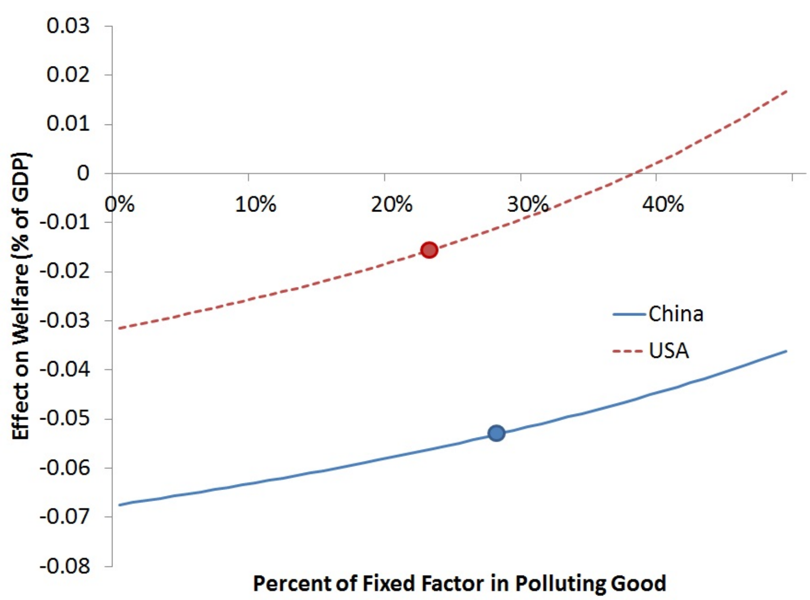
We next examine the slopes of these lines, reflecting the reduction in cost of the policy reform as the informal sector grows in importance in each economy. Since the magnitude of movement from the informal sector to the formal one operates by elasticities, a larger informal sector induces a greater expansion of the formal sector. This is seen in the figure through the upward slopes of the lines.

Finally, we have indicated the point on each of the lines corresponding to the calibrated size of the shadow economies in the U.S. and China in our central case. The larger shadow economy in China cuts the cost in China much more than it would in the U.S., though we see that this effect alone is not enough to reverse the ranking of costs; the tax is still more costly in China. It is useful to note here, however, that the size of China's informal economy is small relative to some other developing countries that are poised to become major carbon emitters.

3.3.2 Ricardian Rents

We next consider in isolation the presence of a fixed factor in the production of fossil energy. The results appear in figure 2 and again are for a fixed emissions reduction of 10%.

Figure 2: The Effect of Ricardian Rents on the Cost of Carbon Emissions Cuts



By construction, the baseline intercepts will be the same as in Figure 1 with the slopes now representing the effect of introducing a fixed factor in energy production. In this case the cost savings are roughly parallel, with the line for the U.S. slightly steeper than that for China. The effect stems from the ability of energy taxes to act as a surrogate tax on Ricardian rents; it is more important when the gap between the pre-existing tax and the tax on the fixed factor is larger.

We again include two points indicating our central calibration. China's combined oil, natural gas, and coal production occupies about 5 percentage points more of its energy sector than the same sectors in the United States. When considering just this factor, the U.S. receives a larger reduction in costs than China since the gap between the pre-existing tax and the tax on the fixed factor starts at a higher level.

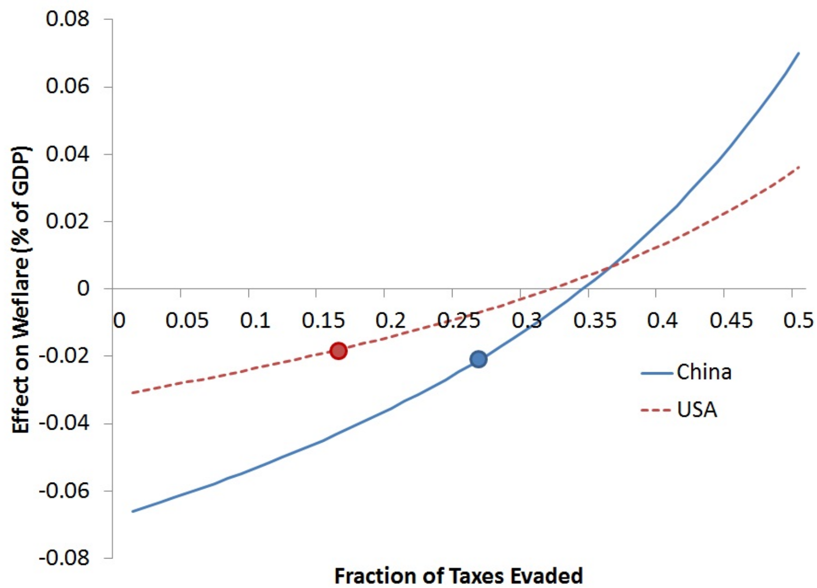
3.3.3 Tax Evasion

Finally, we consider the existence of costly tax evasion following the same approach in Figure 3.

Now costs in China fall more quickly with respect to the degree of tax evasion than they do in the U.S. This is because China's polluting sector is larger, so relatively larger cuts in the pre-existing tax are possible for the same 10% reduction in emissions. Since spending on tax evasion is proportionate to the pre-existing tax, greater tax cuts in China result in greater savings with respect to spending on tax evasion.

The difference between the countries is further sharpened when considering estimates of existing tax evasion, indicated by the points on each line. The combined steeper slope and greater baseline tax evasion in China bring the costs very close together.

Figure 3: The Effect of Tax Evasion on the Cost of Carbon Emissions Cuts



3.3.4 Combined Results

We now turn to our central simulation results, bringing together all three of the effects above. Table 2 displays the results and key mechanisms for a fixed 10% cut in carbon emissions in both countries using our central case parameters in table 1. Our calibration implies that cutting carbon emissions by 10% requires an approximately 21% energy tax in both China and the U.S. The size of the informal sector shrinks more in China than in the U.S., reflecting the greater starting size of the informal sector in China, and Ricardian rents are reduced by about 15% in China and 13% in the U.S. (reflecting the more closely matched slopes in Figure 2). The real cost of tax evasion declines in each country, again with a steeper decline in China. Importantly, the equivalent variation for this tax change is positive in both countries indicating that gross welfare gains are possible from the policy.

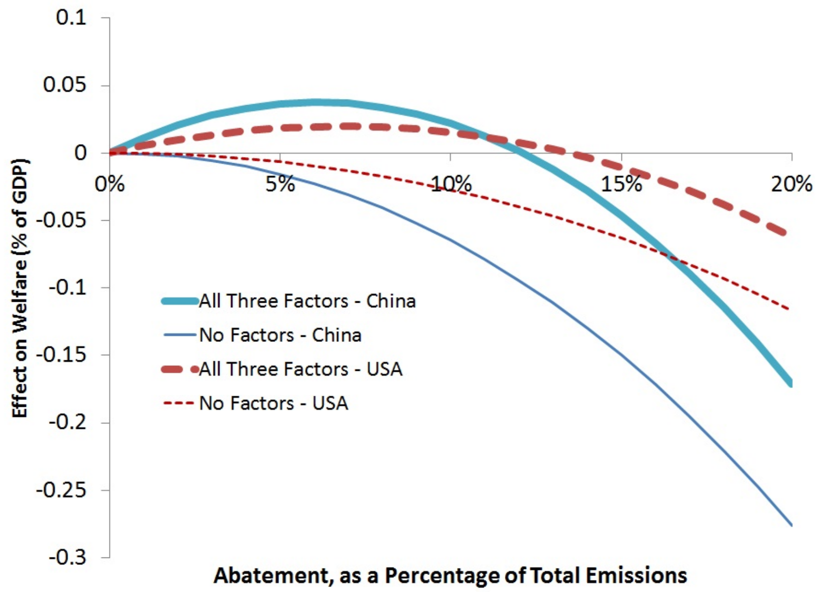
We next consider the way costs change over a range of targeted emissions reductions, no longer fixing them at 10%. Figure 4 illustrates our results with the horizontal axis

Table 2: Simulation Results for a 10% Cut in Carbon Emissions

	China	U.S.
Size of carbon emissions reduction	10%	10%
Energy tax rate (initial rate)	0.21 (0.00)	0.21 (0.00)
Labor tax rate (initial rate)	0.22 (0.24)	0.41 (0.42)
Informal sector		
Change in formal labor (initial size)	0.39 (98.3)	0.12 (99.7)
Change in informal labor (initial size)	-0.16 (7.1)	-0.04 (4.3)
Ricardian rents		
Change in rents (initial size)	-0.45 (3.01)	-0.14 (1.10)
Tax evasion		
Change in labor tax evasion (initial rate)	-0.2% (15.3%)	-0.02% (9.3%)
Change in energy tax evasion (initial rate)	7.5% (0%)	4.3% (0%)
Change in evasion expenditure (initial expenditure)	-0.03 (0.4)	-0.01 (0.4)
Equivalent variation as percentage of GDP	0.022%	0.015%

varying the degree of emissions abatement between zero and 20%.

Figure 4: Effect of All Factors Combined on the Cost of Carbon Emissions Cuts



Baseline Cost Without Informality, Fixed Factors, or Evasion

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, exponentially increasing in abatement, and more than twice as large in China as in the U.S. This reflects the greater energy intensity of China's economy and reproduces the common perception that carbon taxes would be more painful for China than the U.S.

Full Model

The thick dashed line represents equivalent variation in the U.S. when all three of the factors (the informal economy, Ricardian rents, and costly tax evasion) have been introduced together. It lies everywhere above the baseline cost and, for emissions reductions up to 13%, a gross welfare benefit from the policy is realized. This suggests that the optimal carbon tax lies above the Pigouvian level, even in an economy with minimal tax distortions like the United States.[13] Note that our simulations are gross of the environmental benefits of a carbon tax. The results suggest that carbon taxes should play a role in the optimal tax system even when no environmental damages are present.

Turning to China, the thick solid line represents equivalent variation when all three factors are considered. Again, this lies above the baseline for all abatement targets in the plot. The improvement that is realized in costs is much larger for China than the U.S. The effect is strong enough that the costs ranking is reversed for all abatement targets up to 12%. Overall this can be thought of as reflecting a greater set of pre-existing tax distortions in the Chinese economy, resulting in much greater room for welfare gains when energy tax revenue is recycled. The combination of effects in China mean that emissions reductions up to 13% can be achieved with negative gross costs, and the tax system (again gross of environmental benefits) is optimized with a reduction in emissions of about 7%.

For much larger reductions in emissions, 36% and above, we find that the cost of abatement is higher in the full model. This comes from our introduction of Ricardian rents: the presence of rents reduces costs initially (through the mechanism above) but it also implies that very large taxes are needed to achieve deep cuts in emissions (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 dynamic whereby additional reductions in carbon emissions over time would likely continue to be subject to a double dividend over a larger range.

[13]In models where the social external cost of carbon is modeled, our results imply that the optimal tax on carbon should lie above this cost.

When considering the other two factors separately (tax evasion and the informal sector) the cost gains we identify persist at even the highest levels of abatement.

3.4 Sensitivity Analysis

In this section we consider several alternative models and parameterizations that highlight the way each of the three factors we study enters in the two economies. The results appear in Table 3 with values displaying the gross welfare costs as a fraction of the baseline. Each number in the table represents a separate simulation where emissions are cut 10% and negative values indicate cases with gross welfare gains.

In each row, where we vary the way features of the model are included, we also consider two possible levels for the pre-existing factor tax burden in each country. The "high" cases refer to pre-existing tax burdens of 24% and 41% in China and the U.S. respectively. These are drawn from long-run government expenditures and form the basis for the central estimates above. We argue these rates are most appropriate in that the overall tax burden in an economy will reflect government spending in the long run. The "low" columns refer to pre-existing tax rates of 19% in China and 25% in the U.S., instead calculated using taxes collected (Heritage Foundation 2014). Using these lower rates produces smaller gains in welfare since the key mechanism at work involves recycling revenue against pre-existing taxes; the reversal of the cost ranking between China and the U.S. is preserved even as costs increase.

The first three rows explore cases where each of an informal sector, rents, and tax evasion are added in isolation. We find that the presence of an informal sector has the greatest impact on welfare in both countries. The second most important factor in each is tax evasion.

In the second group of cases we include two factors at a time to see how omitting

Table 3: Sensitivity Analysis

	China		U.S.	
Pre-existing labor tax	Low	High	Low	High
No factors	-6.45	-6.74	-2.71	-3.14
Simulations isolating a single factor				
Informal economy alone	-3.35	-2.62	-1.69	-1.09
Ricardian rents alone	-5.87	-5.30	-2.25	-1.61
Tax evasion alone	-4.38	-4.36	-2.20	-2.37
Simulations combining two factors				
Ricardian rents and tax evasion	-3.41	-2.55	-1.71	-0.87
Informal economy and tax evasion	-1.71	-0.83	-1.26	-0.51
Informal economy and Ricardian rents	-1.67	0.40	-0.94	1.11
Alternative parameterizations				
Central estimate	0.16	2.26	-0.52	1.57
Low informal economy	-0.51	1.34	-0.74	1.10
High informal economy	5.51	9.68	1.26	5.41
Low Ricardian rents	-0.82	0.63	-0.80	0.78
High Ricardian rents	1.37	4.31	-0.17	2.56
Low tax evasion	-1.18	0.88	-0.19	1.95
High tax evasion	2.01	4.23	-0.73	1.34

Notes: Each value refers to the welfare cost of a revenue neutral policy that raises the energy 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.

a given factor impacts our analysis.[14] We find that omitting tax evasion has the least impact on the magnitudes of our results. This may come in part from the way we model tax evasion: we assume that all shadow economy activity was taken out of tax evasion, and so when it is omitted some of that activity remains as part of the informal sector.

In the third set of cases we include all three factors but now alter input parameters to the model. First, we test low and high parameterizations of the informal economy 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 test 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) we consider values of 0.15 and 0.3. Finally, we consider low and high values for tax evasion in China (15% in the central case) of 5% and 25%, and low and high values in the U.S. (9% in the central case) of 5% and 15%.

These are the key parameters governing the strength of effects in our model and so costs shift significantly, but we note that our primary conclusions remain intact even for large deviations in the calibration. First, in China there continues to be a gross welfare gain in nearly all simulations. A gross welfare gain is also present in the U.S. when high pre-existing tax rates are assumed, and very large cuts in cost are present even with lower pre-existing tax rates. Second, the cost of environmental reform is lower (or gains larger) in China than the U.S. for almost all sets of simulations, preserving the reversal in cost that we identify above.

[14] It may be possible in some contexts for certain effects to be absent. For example, in China, tax evasion may be partially accomplished through political means and relationships rather than firms paying a real cost. In this case, the real cost of tax evasion is lower, and considering the cost of a two-factor model may be more appropriate.

3.5 Additional Dimensions

The tax systems and pre-existing environmental damages in OECD and developing countries also differ in many dimensions outside the scope of our model. Some of these, for example interactions between trade and carbon policy, may be more important in China but can be addressed through policy provisions like border tax adjustments. We believe that a range of other important differences across countries are likely to further compound the advantages of carbon taxes in developing countries that we describe above:

First, gains in worker productivity from reduced air pollution (see Graff Zivin and Neidell [2012]) will enter importantly to reduce the welfare costs of a carbon tax and are likely to be especially large in developing countries. In China, for example, the high starting levels of local air pollution and greater fraction of the population employed in manually intensive work could create greater productively gains 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 than the U.S. (IMF 2014), making each unit of reduction more important in terms of local air pollution benefits.

A second factor which could compound the difference in optimal energy taxes is induced technological change, as in Popp (2002) where higher energy prices lead to increases in the number of energy efficiency patents. To the extent baseline energy efficiency is lower in China (Yao et al 2012), advances in efficiency could have a proportionally greater impact on growth. Additional empirical work in this area could be used to extend the model above.

Finally, tax-favored consumption, as documented in Parry and Bento (2000), is another important dimension along which developing countries may differ. Here there is less empirical evidence on differences across countries, but to the extent tax systems in developing countries are less able to produce even 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 energy taxes overall.

We have focused exclusively on the cost side of policy in our work above, though it is clear that important differences also exist in environmental benefits. To the extent benefits (particularly local co-benefits) are also greater in developing countries the optimal tax rate would be further increased.[15] Aunan et. al (2007), for example, explore co-benefits 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. The potential for significant reduction in this burden further compounds the effect we identify above.[16]

4 Conclusion

The possibility that the implementation of a carbon tax in China could simultaneously reduce carbon dioxide emissions and enhance economic growth could radically alter the dynamics of what is both optimal and possible in terms of a global climate agreement (Aldy and Stavins, 2007). Our results suggest that such a case can be made and iden-

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

[16]Williams (2003) shows how improving worker health could instead increase aggregate leisure time (furthering the pre-existing distortion in labor supply) potentially acting in the opposite direction on welfare.

tifies the source of several important differences in policy cost between China and the U.S. We employ a standard framework for analysis of the double-dividend hypothesis and combine three key factors identified in the literature: the presence of an informal sector, existence of Ricardian rents in the energy resource sector, and tax evasion. Each of these factors enters more importantly in China than in the United States, providing an especially strong case for carbon taxes in China. Because implementation details matter, we also hope our work encourages efforts to identify the impact of changing particular taxes and of what sectors of the economy are likely to experience substantial impacts in China.[17]

Other large developing countries like India are also poised to become major carbon dioxide emitters; the factors we explore may be even more important there and could be identified with additional empirical and modeling work. The range of reductions over which China would experience a strong double-dividend from a revenue neutral move away from current distorting taxes toward a carbon tax is clearly large enough in our simulation for our results to be policy relevant. They are also large enough to justify a more comprehensive examination of the nature of the economic gains and the practicalities of the economy-wide implementation of a carbon tax in China. Finally, our simulation results also call for a degree of caution: despite these three factors, the tradeoff between economic efficiency and environmental quality looms large when contemplating the very large reductions in carbon emissions called for in many international forums.

[17] For work along this line in the United States see three recent Resources for the Future discussion papers (Goulder and Hafstead, 2013; Metcalf, 2013; Williams, et al., 2014).

References

Aldy, J.E. and R.N. Stavins, eds. 2007. *Architectures for Agreement: Addressing Global Climate Change in the Post-Kyoto World*. New York: Cambridge Economic Press.

Aunan, K., T. Berntsen, D. O'Connor, T. H. Persson, H. Vennemo, F. Zhai. 2007. "Benefits and costs to China of a climate policy." *Environment and Development Economics* 12: 471-497.

Bento, A.M. and M. Jacobsen. 2007. "Ricardian rents and economic policy: the double-dividend hypothesis." *Journal of Environmental Economics and Management* 53(1): 17-31.

Bento, A., M. Jacobsen, A. Liu. 2014. "Environmental policy in the presence of an informal sector." Working paper, University of California, San Diego.

Bovenberg, A.L. and R.A. de Mooij. 1994. "Environmental levies and distortionary taxation." *American Economic Review* 84: 1085-1089.

Bovenberg, A.L. and L.H. Goulder. 1996. "Optimal environmental taxation in the presence of other taxes: general equilibrium analyses." *American Economic Review* 86: 985-1000.

Bovenberg, A. and L.H. Goulder. 2002. "Environmental taxation and regulation" in A.J. Auerbach and M. Feldstein, eds., *Handbook of Public Economics* 3: 1471-1545. Amsterdam: Elsevier.

Carbone, J.C. and V.K. Smith. 2008. "Evaluating policy interventions with general equilibrium externalities." *Journal of Public Economics* 92(5): 1254-1274.

Fraser, I. and R. Waschik. 2013. "The double dividend hypothesis in a CGE model: specific factors and the carbon base." *Energy Economics*, 39: 283-295.

Fullerton D. and G.E. Metcalf. 2001. "Environmental controls, scarcity rents, and pre-existing distortions." *Journal of Public Economics* 80:249–267.

Fullerton, D., A. Leicester, and S. Smith. 2010. "Environmental taxes," in *Dimensions of Tax Design*, Oxford: Oxford University Press.

Gordon, R. and S. Bo Nielsen. 1997. "Tax evasion in an open economy: Value-added vs. income taxation." *Journal of Public Economics*, 66:173-197.

Goulder, L.H. 1995. “Environmental taxation and the ‘double dividend’: a reader’s guide.” *International Tax and Public Finance*, 2:157–198.

Goulder, L.H. and Marc Hafstead. 2013. “Tax Reform and Environmental Policy: Options for Recycling Revenue from a Tax on Carbon Dioxide.” RFF Discussion Paper 13-31, October 2013.

Goulder, L.H. and R.C. Williams. 2003. “The substantial bias from ignoring general equilibrium effects in estimating excess burden and a practical solution.” *Journal of Political Economy*, 111(4): 898–927.

Graff Zivin, J. and M. Neidell. 2012. “The impact of pollution on worker productivity.” *The American Economic Review* 102: 3652-3673.

Heritage Foundation. 2014. *2014 Index of Economic Freedom: Promoting Economic Opportunity and Prosperity.*

International Monetary Fund. 2014. *Getting Energy Prices Right: From Principle to Practice*. Washington, D.C.: International Monetary Fund.

Liu, A.A. 2013. “Tax evasion and optimal environmental taxes.” *Journal of Environmental Economics and Management* 66(3): 656-670.

Mankiw, N.G. 2009. “Smart taxes: An open invitation to join the Pigou club.” *Eastern Economic Journal* 35(1): 14-23.

Metcalf, G. E. 2013. “Using the Tax System to Address Competition Issues with a Carbon Tax.” RFF Discussion Paper 13-30, October 2013.

Metcalf, G. E., and D. Weisbach. 2009. “The design of a carbon tax.” *Harvard Environmental Law Review* 33: 499-556.

Parry, I. W. 1995. “Pollution taxes and revenue recycling.” *Journal of Environmental Economics and Management* 29(3): S64-S77.

Parry, I. W., and A. M. Bento. 2000. “Tax deductions, environmental policy, and the ’double dividend’ hypothesis.” *Journal of Environmental Economics and Management* 39: 67-96.

Parry, I. W., J. Norregaard, and D. Heine. 2012. “Environmental Tax Reform: Principles from Theory and Practice.” *Annual Review Resource Economics* 29(3): S64-S77.

Pearce, D. 1991. "The Role of Carbon Taxes in Adjusting to Global Warming." *Economic Journal* 101(407): 938-948.

Popp, D. 2002. "Induced Innovation and Energy Prices." *The American Economic Review* 92(1): 160-180.

Poterba, J.M. 1991. "Designing a Carbon Tax." in *Economic Policy Responses to Global Warming*. R. Dornbusch and J.M Poterba, eds. Cambridge, MA: MIT Press.

Schneider, Friedrich. 2005. "Shadow Economies of 145 Countries all over the World: What Do We Really Know?" Center for Research in Economies, Management, and the Arts Working Paper No. 2005-13.

Slemrod, J. 2007. "Cheating ourselves: the economics of tax evasion." *Journal of Economic Perspectives* 21 (1): 25-48.

U.S. Energy Information Administration. 2013. *International Energy Outlook 2013*. Washington D.C.: U.S. Energy Information Administration.

Williams, R.C. 2002. "Environmental tax interactions when pollution affects health or productivity." *Journal of Environmental Economics and Management* 44: 261–270.

Williams, R.C. 2003. "Health effects and optimal environmental taxes." *Journal of Public Economics* 87: 323–335.

Williams, R.C., Hal Gordon, Dallas Burtraw, Jared Carbone, and Richard Morgenstern. 2014. "The Initial Incidence of a Carbon Tax across Income Groups." RFF Discussion Paper 14-24, August 2014.

Wood, I. 2011. "What fuels presidential approval: the link between gas prices and presidential approval ratings." http://www.centerforpolitics.org/crystalball/articles/ITW2011042801/ accessed September 2014.

World Bank. 2007. *Cost of Pollution in China: Economic Estimates of Physical Damages*. Washington D.C.: The World Bank.

World Bank. 2011. *The Changing Wealth of Nations: Measuring Sustainable Development in the New Millennium*. Washington D.C.: The World Bank.

Yao, Shujie, Dan Luo and Tyler Rooker. 2012. "Energy Efficiency and Economic Development in China." *Asian Economic Papers* 11(2):99-117.

Appendix: Derivation of Welfare Formulas

Combining equations (9) and (10) allows us to restate the household optimization problem as:

$$W = u\left(G, S, \overline{L} - L\right) - \phi\left(E\right) - \lambda\left[p_G G + p_S S - L - H - \pi_{FF} - \pi_{SN}\right] \tag{23}$$

Totally differentiating with respect to τ_E yields:

$$\frac{1}{\lambda}\frac{dW}{d\tau_E} = -\frac{1}{\lambda}\phi^{'}\left(E\right) - \frac{dp_G}{d\tau_E} - \frac{dp_{SM}}{d\tau_E}S + \pi_{FF} + \pi_{SN} \tag{24}$$

We take the derivatives of equations (12) and (13):

$$\frac{dp_G}{d\tau_E} = \frac{d\left(\left(1-\epsilon_L\right)\tau_L\right)}{d\tau_E} + \frac{E}{G}\left[\frac{d\left(\left(1-\epsilon_E\right)\tau_E\right)}{d\tau_E}\right] + \gamma_L^{'}\left(\tau_L\right) \tag{25}$$

$$\frac{dp_{SM}}{d\tau_E} = \frac{d\left(\left(1-\epsilon_L\right)\tau_L\right)}{d\tau_E} + \gamma_L^{'}\left(\tau_L\right) \tag{26}$$

Similarly, we take the total derivative of the government budget constraint, equation (7), and set it to zero to reflect revenue neutrality:

$$\begin{aligned} & -\frac{d\left(\left(1-\epsilon_L\right)\tau_L\right)}{d\tau_E}\left(L_G + E_G + L_{SM}\right) - \frac{d\left(\left(1-\epsilon_E\right)\tau_E\right)}{d\tau_E}E \\ & \qquad = \left(1-\epsilon_L\right)\tau_L\frac{d\left(L - L_{SN}\right)}{d\tau_E} + \left(1-\epsilon_E\right)\tau_E\frac{dE}{d\tau_E} \end{aligned} \tag{27}$$

Finally, substituting back in to equation (24) yields equation (15) in the main text.