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STUCK IN A CORNER? CLIMATE POLICY IN DEVELOPING COUNTRIES

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Much of the capital equipment used in developing countries is created in the OECD and, thus, is designed to make optimal use of the relative supplies of capital, labor, and energy in these developed countries. However, differences in capital–labor ratios between developed and developing countries create a mismatch between the energy requirements of this capital and developing countries' optimal levels of energy intensity. Using a calibrated macroeconomic model, this paper analyzes the implications of this mismatch for climate policy. I find that using capital equipment with "inappropriate" energy intensity has sizeable consequences for both the effectiveness and the welfare cost of climate policies in developing countries.

Keywords: Climate Policy, Macroeconomics, Carbon Tax, Development

1. INTRODUCTION

Firms in developing countries do not always use capital equipment with energy intensity that is "appropriate" for their resources. Most production technologies make optimal use of the capital, labor, and energy inputs of the richer economies because weak intellectual property rights induce entrepreneurs to target their innovation toward the developed countries' needs [Acemoglu and Zilibotti (2001), Basu and Weil (1998)]. However, cross-country differences in capital–labor ratios lead to different demands for energy intensity. These differences imply that the energy intensity embodied in capital equipment designed for developed countries could be suboptimal for use in developing countries. This paper develops a macroeconomic model to explore the effects of this suboptimality for climate change mitigation. I find that using capital equipment with inappropriate energy intensity could have sizeable implications for both the effectiveness and welfare cost of climate policy in developing countries.[1]

I extend the standard neoclassical growth model to incorporate the mechanisms through which inappropriate technology could impact climate policy outcomes in developing countries. A representative, profit-maximizing firm produces

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output from capital, labor, and fossil energy. I interpret the capital–labor ratio of this representative firm as a measure of economic development. Consistent with the empirical evidence, I assume that the capital–labor ratio is higher in more developed countries.

I allow for the possibility that a firm's energy intensity is inappropriate for its level of development by imposing an upper bound on the energy intensity of capital in the production process (i.e., the ratio of fossil energy to capital). This upper bound limits the substitutability between capital and energy. For example, a firm can reduce the energy efficiency components of a car and purchase a car with less capital that uses more energy to produce the same transportation. However, there are limits to this substitution; very low capital cars with very high energy needs (e.g., fuel economy equal to 1 mile per gallon) are not available. I show analytically that the upper bound on energy intensity could bind in less-developed countries (i.e., countries with small capital–labor ratios). When the upper bound binds, a firm's energy intensity is inappropriate for its capital–labor ratio, and its optimal energy use is a corner solution. I define a country to be "in the corner" if the upper bound on energy intensity binds for its representative firm.

I calibrate the model and analyze the effects of two standard approaches for climate change mitigation: (1) a carbon price (e.g., a carbon tax) and (2) a quantity target (e.g., a cap-and-trade system). I introduce each of these policies into the model and analyze the short- and long-run effects of the policy as the country develops endogenously along its neoclassical growth path. I compare the welfare costs and effectiveness across countries that are at different levels of development when they first implement the policy. I find that the results of these policies are considerably different based on whether or not the country is in the corner when it introduces the policy.

Beginning with the carbon tax results, both the effectiveness (in terms of emissions reduction) and the welfare cost of the tax are smaller for countries that are in the corner when they introduce the policy. Since a carbon tax raises the price of energy, it increases the firm's incentives to economize on energy use and, thus, can move a firm from the corner where the constraint on energy intensity binds, to the interior. However, if the carbon tax is not large enough to remove the firm from the corner, then it will not incentivize any reduction in emissions because the upper bound on energy intensity continues to bind under the tax. In general, the need for the tax to remove the firm from the corner, in addition to incentivizing the firm to reduce emissions, decreases the effectiveness of the tax for developing countries in the corner, resulting in a smaller reduction in emissions. Smaller reductions in emissions decrease the distortions in behavior from the tax, lowering the welfare costs of the policy.

In contrast to the carbon tax, the percentage reduction in emissions under the quantity target is the same, by design, for all countries. Thus, the effectiveness of the quantity target is independent of whether or not the country is in the corner when it introduces the policy. However, the welfare costs of a quantity target are substantially higher for countries in the corner because the quantity target amplifies the distortion to energy intensity already created by the upper bound. Combined, the carbon-tax and quantity-target results imply that the appropriateness of a firm's energy intensity for its capital–labor ratio can have a substantial impact on climate policy outcomes.

Although the model predicts zero responsiveness to a change in energy prices in a country whose representative firm is stuck in a corner, empirically, we should not observe zero responsiveness because firms are different. Even if the average or representative firm in a country is stuck in the corner, some firms are not in the corner, and those will respond. However, the fact that many firms do not respond at all should make the price elasticity of energy demand smaller for countries whose representative firm is stuck. Studies on energy demand elasticities vary considerably in terms of the methodology, time period, energy type, and sector. As a result, it is hard to reach consensus on the magnitude of different energy demand elasticities in the literature. However, consistent with the results in this paper, Bose and Shukla (1999) estimate that the long-run price elasticity of demand for electricity in India is −0.26, whereas Bernstein and Griffin (2006) estimate that this elasticity in the United States is −0.97. Therefore, these two studies support the hypothesis that energy demand is less elastic in developing countries.

Two developing countries that are key emitters in the current economy are India and China. I find that for most plausible values of the upper bound on energy intensity, India's level of development (measured by its capital–labor ratio) is in the corner, whereas China's is just beyond the corner. All else constant, these results imply that the effectiveness and welfare cost of a carbon tax would be considerably smaller in India than in China or the United States. In contrast, the welfare cost of an abatement target would be considerably larger in India than in China or the United States. Understanding these countries' welfare costs is important for designing an incentive-compatible global emissions agreement.

The notion of fairness across countries is an ongoing issue in international climate negotiations. These results suggest that if policy makers strive to design a climate policy that is "fair" in the sense that it equalizes the welfare cost, it should include larger carbon taxes or smaller abatement targets for developing countries in the corner. For example, I find that for some specifications, the upper bound on energy intensity implies that the carbon tax in India must be 25 percent larger than the tax in the United States for India to incur the same welfare cost from the policy as the United States.

This paper builds on the growing literature, which applies macroeconomic models to study climate policy. For examples, see Golosov et al. (2014), Krusell and Smith (2009), Hassler and Krusell (2012), and Nordhaus and Boyer (2000). Like these papers, this paper develops a model of the macroeconomy, energy, and climate policy. However, this previous work abstracts from the effects of appropriate technology in developing countries, the focus of the present analysis.[2]

This paper also relates to the literature on the spatial variance in the welfare cost of climate policy. For example, Chichilnisky and Heal (1994) and Sheeran (2006) suggest that developing countries experience higher welfare costs because they have a higher marginal utility of income. On the environmental side, Brock et al. (2014) show that the welfare effects of climate policy could vary due to the differences in thermal transport across latitudes. In line with this earlier work, this paper demonstrates that inappropriate technology in developing countries can also lead to substantial variance in the welfare costs of climate policy across countries.

The paper proceeds as follows: Section 2 develops a simple static model to compare the one-period impact of climate policies across countries at different levels of economic development. Section 3 incorporates the static model into a dynamic neoclassical growth model to analyze the long-run welfare costs of introducing climate policy in countries at different initial stages of economic development. Section 4 evaluates the robustness of the results to different modeling assumptions, and Section 5 concludes.

2. STATIC MODEL

I begin with a simple static model to highlight the mechanisms through which inappropriate technology can affect climate policy. I measure a country's level of economic development by the ratio of its existing capital stock, K, relative to its supply of effective labor, AL. I refer to this quantity, $\frac{K}{AL}$, as the capital–labor ratio.[3] I focus on how the existing capital–labor ratio affects the firm's energy decisions in response to climate policy. I interpret these results as indicative of how the one-period effects of the policy vary across countries that are at different points on their neoclassical growth paths, and, thus, at different stages of economic development.

2.1. Firm

A representative firm combines fossil energy, E, capital, K, and labor, L, to produce output, Y. The production technology is Cobb–Douglas with an upper bound on the energy intensity of capital,[4]

$$Y = K^{\alpha} E^{\theta} (AL)^{1-\alpha-\theta} \quad \text{s.t.} \quad \frac{E}{K} \leq X. \tag{1}$$

Parameters α, θ, and $1-\alpha-\theta$ are the factor shares of capital, energy, and labor, respectively. Variable A is exogenous technological progress.

A frequent critique of the Cobb–Douglas specification is the high substitutability between capital and energy. A piece of capital equipment often has a fixed amount of fossil energy required for its operation. For example, cars require a fixed amount of gas, coal boilers require a fixed amount of coal. These energy requirements suggest that more capital requires more energy, not less, and thus, are more consistent with a Leontief production technology than with Cobb–Douglas. However, firms can also invest in special types of capital that reduce the fossil energy necessary to operate their machines and buildings. Examples include hybrid-breaking technologies in cars, more efficient coal boilers, and wind turbines instead of coal boilers. These types of capital investments reduce the firm's energy use and imply that there is some substitutability between capital and energy.

One approach to modeling firm production would be to differentiate between the firm's typical investments in machines and buildings and additional investments it makes to reduce its energy use. In the appendix, I consider an alternative production function that allows firms to invest in special capital equipment to reduce their energy use but otherwise assumes extreme nonsubstitutability between regular capital and energy.[5] In this appendix, I model production as Leontief between capital and energy, but firms can affect the Leontief parameter governing the required input ratios through a special type of energy-saving investment. I show that for reasonable functional forms, such a formulation is equivalent to a Cobb–Douglas production function with an upper bound on the energy intensity of capital, $\frac{E}{K} \leq X$.

The upper bound reflects that there is a limit to how much raising energy for a given amount of capital can increase output. For example, a firm could produce transportation using capital (a car) and energy (gasoline). The firm could reduce the energy efficiency components of the car and produce the same transportation with a cheaper car (i.e., less capital) that used more energy. For a second example, consider a firm that produces electricity using capital (a coal boiler) and energy (coal). The firm could reduce the energy efficiency components of the boiler and produce the same electricity with a cheaper boiler (i.e., less capital), which used more coal. However, there is a limit to how much firms can substitute the energy input for capital. Very cheap (low capital) cars with very low fuel economy (say equal to one mile per gallon) are not available. Similarly, very cheap (low capital) boilers with very high heat rates (say equal to millions of BTUs per kilowatt hour) are also not available. The upper bound on the energy intensity of capital captures these limits to substitutability.

2.2. Optimization

The firm takes prices as given and chooses the production factors to maximize profits, subject to the upper bound. The firm's optimization problem is

$$\max_{E,K,L} \left\{ K^{\alpha} E^{\theta} (AL)^{1-\alpha-\theta} - RK - wL - P(1+\tau)E \right\} \quad \text{subject to} \quad \frac{E}{K} \leq X. \tag{2}$$

Variable w denotes the wage. The rental rate of capital, R, is the sum of the risk-free interest rate, r, and the depreciation rate, δ, $R = r + \delta$. Note that while the representative firm chooses capital and labor, as well as energy, in equilibrium, the wage and the rental rate adjust to ensure that the existing capital stock is fully utilized and the existing labor force is fully employed.

Parameter P is the exogenous energy price. The country behaves as a small open economy with respect to energy. Energy is imported in exchange for final good with zero trade balance in every period. The small open economy assumption abstracts from the potential general equilibrium effects of climate policy on energy prices. However, global energy supplies and prices are not within any single country's control. Moreover, most countries have very limited market power with respect to energy prices, suggesting that the general equilibrium effects from a unilateral climate policy are likely to be small. Section 4 discusses the implications of this simplification for the main results.[6]

Variable τ represents a carbon tax. A carbon tax is essentially a tax on energy use, since the majority of all greenhouse gas emissions come from fossil energy combustion (IPCC, 2014). For analytical tractability, I model a carbon tax as a percent of the energy price instead of as an additive tax per unit of energy consumed. This formulation is equivalent to a per unit tax because the energy price is constant. All carbon tax revenues are returned lump sum to the household through government transfers, T.

Combining the firm's first-order conditions with respect to fossil energy and capital yields its optimal level of energy intensity:

$$\frac{E}{K} = \begin{cases} X & : \lambda > 0 \\ \left(\frac{\theta}{\alpha}\right) \frac{R}{P(1+\tau)} & : \lambda = 0, \end{cases} \tag{3}$$

where λ is the shadow value of the constraint. If the price of capital in a country is high relative to the world price of energy, then the country optimally chooses to use more energy per unit of capital. A developing country is characterized by a low level of capital, which implies a high price of capital. Thus, equation (3) implies that optimal energy intensity in capital-poor (developing) countries exceeds optimal energy intensity in capital-rich (developed) countries.

To demonstrate this intuition formally, observe that when the constraint does not bind ($\lambda = 0$), the firm's first-order condition for capital implies that the price of capital is

$$R = \alpha \left(\frac{E}{K}\right)^{\theta} \left(\frac{K}{AL}\right)^{-(1-\alpha-\theta)}. \tag{4}$$

Equation (4) shows that a country's price of capital is decreasing in its capital–labor ratio due to the standard diminishing returns in the Cobb–Douglas production function. Combining equation (4) with equation (3) yields the country's optimal energy intensity as a function of its capital–labor ratio:

$$\frac{E}{K} = \begin{cases} X & : \lambda > 0 \\ \left(\frac{K}{AL}\right)^{-\left(\frac{1-\alpha-\theta}{1-\theta}\right)} \left(\frac{\theta}{P(1+\tau)}\right)^{\frac{1}{1-\theta}} & : \lambda = 0. \end{cases} \tag{5}$$

Equation (5) confirms the earlier intuition; optimal energy intensity is higher in less-developed countries (i.e., countries with lower capital–labor ratios).

There exists a threshold capital–labor ratio below which the upper bound on energy intensity binds. Equating optimal energy intensity [equation (5)] with its

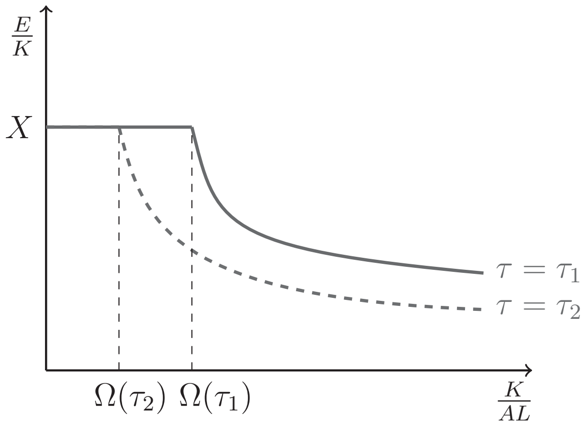

FIGURE 1. Constrained optimal energy intensity for different tax rates.

upper bound, X, yields this threshold:

$$\Omega(\tau) \equiv X^{\frac{1-\theta}{1-\alpha-\theta}} \left(\frac{\theta}{P(1+\tau)} \right)^{\frac{1}{1-\alpha-\theta}}. \tag{6}$$

The threshold is decreasing in the tax, $\Omega'(\tau) < 0$, since higher energy prices reduce optimal energy intensity. In particular, the before-tax threshold (i.e., the threshold with a carbon tax of zero, $\Omega(0)$) is bigger than the after-tax threshold, $\Omega(0) > \Omega(\tau > 0)$.

If the capital–labor ratio is above the threshold, then the firm's input choices are unconstrained. However, below the threshold, the firm's energy intensity is a corner solution; all else constant, additional fossil energy will not increase firm output. Firms in this region would like to produce with cheaper and less energy-efficient capital than is available. Thus, the constraint on energy intensity binds in countries with development levels below $\Omega(\tau)$.

Figure 1 demonstrates this intuition graphically. The figure plots the firm's optimal constrained energy choice as a function of the capital–labor ratio for two different tax rates, τ_1 and τ_2, with $\tau_2 > \tau_1$. Increasing the tax rate reduces the threshold value of the capital–labor ratio and lowers the optimal value of energy intensity at all points above the threshold.

2.3. Effects of Climate Policy

I explore the implications of the threshold for countries that implement a climate policy at different stages of development, which I define as different values of the capital–labor ratio. I consider two climate policies: (1) a uniform and constant carbon tax across countries at all stages of development, and (2) a uniform abatement (quantity) target across countries at all stages of development. To measure abatement in period t by a representative firm in a country with capital–labor ratio j, I compare the firm's optimal energy use (and hence emissions) with and without the carbon tax in place. Abatement is the percent reduction in the firm's emissions as a result of the carbon tax.

2.3.1. Uniform carbon tax. I analyze the effects of a uniform carbon tax, τ, on energy use in countries at different levels of development. The existence of the capital–labor threshold violates the standard result that a very small carbon tax can induce firms to undertake abatement at little or no distortionary cost to the economy. This standard result assumes that the firm is at an interior optimum and, thus, holds for capital–labor ratios above $\Omega(\tau)$. However, a very small carbon tax does not incentivize abatement if a country's capital–labor ratio is below $\Omega(\tau)$.

Rearranging equation (5) and incorporating the upper bound on the energy intensity of capital yields the following condition for firm energy use:

$$E = \begin{cases} KX & : \frac{K}{AL} \leq \Omega(\tau) \\ \left(\frac{AL}{K}\right)^{\frac{1-\alpha-\theta}{1-\theta}} \left(\frac{\theta}{P(1+\tau)}\right)^{\frac{1}{1-\theta}} K & : \frac{K}{AL} > \Omega(\tau). \end{cases} \tag{7}$$

For countries above the before-tax threshold, $\Omega(0)$, the carbon tax, τ, reduces energy use and hence emissions by a factor of $\left(\left(\frac{1}{1+\tau}\right)^{\frac{1}{1-\theta}} - 1\right)$. For countries below the after-tax threshold, $\Omega(\tau > 0)$, the tax leads to zero reduction in emissions. Since the threshold is decreasing in the carbon tax, $\Omega'(\tau) < 0$, there exists a set of countries that are below the before-tax threshold and above the after-tax threshold, $\Omega(\tau > 0) \leq \frac{K}{AL} \leq \Omega(0)$. The tax reduces emissions in this subset of countries by a factor greater than zero but less than $\left(\left(\frac{1}{1+\tau}\right)^{\frac{1}{1-\theta}} - 1\right)$. Thus, the percentage abatement from a carbon tax is (weakly) increasing in the level of development.

2.3.2. Uniform abatement targets across countries. The preceding subsection showed that the level of abatement from a carbon tax increases with the country's level of economic development. In this subsection, I consider the reverse exercise and analyze how the size of the carbon tax necessary to achieve an abatement target varies across countries at different stages of development.

To be concrete, consider a carbon tax designed to achieve an abatement target of b percent in every period. I calculate the size of the tax as function of the capital–labor ratio. In countries with development levels above the before-tax threshold, $\Omega(0)$, a b percent reduction in emissions requires that the firm decrease its energy intensity by b percent from its optimal value with no carbon tax. Thus, the carbon tax in the interior, τ_I, solves

$$\left[(1-b)\,\frac{E}{K}\right]|_{\tau=0} = \left[\frac{E}{K}\right]|_{\tau=\tau_I}. \tag{8}$$

In an interior solution, optimal energy intensity is given by equation (5) with $\lambda = 0$. Therefore, the carbon tax required to attain this reduction in energy intensity

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must solve the following equality:

$$(1-b)\left(\frac{K}{AL}\right)^{-\left(\frac{1-\alpha-\theta}{1-\theta}\right)}\left(\frac{\theta}{P}\right)^{\frac{1}{1-\theta}}=\left(\frac{K}{AL}\right)^{-\left(\frac{1-\alpha-\theta}{1-\theta}\right)}\left(\frac{\theta}{P(1+\tau_I)}\right)^{\frac{1}{1-\theta}}, \quad (9)$$

which yields

$$1+\tau_I=\left(\frac{1}{1-b}\right)^{1-\theta}. \quad (10)$$

The tax is increasing in the stringency of the abatement target and is independent of the capital–labor ratio, provided that the capital–labor ratio is above $\Omega(0)$. This invariance results from the homothetic properties of the Cobb–Douglas production function.

Next, consider the tax necessary to induce firms below $\Omega(0)$ to reduce their emissions by b percent. Below the threshold, the constraint on energy intensity binds and the firm's energy choice is a corner solution. I divide this tax for firms in the corner, τ_C, into two components. The first component of the tax, τ_{C_1} must move the firm from the corner to the interior. Under τ_{C_1}, the optimal *unconstrained* energy intensity is X. Thus, τ_{C_1} solves the following equality:

$$X=\left(\frac{K}{AL}\right)^{-\left(\frac{1-\alpha-\theta}{1-\theta}\right)}\left(\frac{\theta}{P(1+\tau_{C_1})}\right)^{\frac{1}{1-\theta}} \quad (11)$$

which yields

$$1+\tau_{C_1}=X^{-(1-\theta)}\left(\frac{K}{AL}\right)^{-(1-\alpha-\theta)}\left(\frac{\theta}{P}\right). \quad (12)$$

Tax, τ_{C_1}, is decreasing in the capital–labor ratio, since optimal energy intensity is inversely related to economic development. However, although this tax moves the firm from the corner to the interior, it does not incentivize emissions reduction. The second component of the tax, τ_{C_2}, must achieve the abatement target. This second component is the same as the tax in countries with capital–labor ratios greater than $\Omega(0)$, $\tau_{C_2}=\tau_I$. Therefore, the total tax required to attain the abatement target in developing countries below the threshold is $1+\tau_C=(1+\tau_{C_1})(1+\tau_{C_2})$. Thus, larger carbon taxes are required to achieve the abatement target in developing countries with capital–labor ratios below $\Omega(0)$.

3. DYNAMIC MODEL

The preceding section analyzed the one period effects of climate policy on countries at different stages of economic development. This section extends the earlier model to analyze the dynamic effects of climate policy as a country develops endogenously along its neoclassical growth path to reach its long-run equilibrium.

Specifically, I compare the long-run welfare effects of introducing a climate policy for countries at different initial stages of economic development.

3.1. Household

I add the standard household problem to the model to endogenize capital accumulation, and hence, economic development. The economy is inhabited by a representative household with inelastic labor supply, L. The household divides its income between consumption, c, and saving in a risk-free asset, a, to maximize lifetime utility:

$$U = \sum_{t=0}^{\infty} \beta^t \frac{c_t^{1-\sigma}}{1-\sigma}. \quad \mathbf{(13)}$$

Fraction $\frac{1}{\sigma}$ is the intertemporal elasticity of substitution and β is the discount factor. The household performs this optimization subject to the flow budget constraint:

$$c_t + a_{t+1} = w_t L + (1 + r_t)a_t + T_t, \quad \mathbf{(14)}$$

where w and r denote the market wage and risk-free rates, respectively, and T is the income from government transfers.

3.2. Equilibrium

I define a decentralized competitive equilibrium. The individual state variable is asset holdings, a, and the aggregate state variables are the capital stock, K, the labor supply, L^s, and the level of technology, A.

Given an exogenous energy price, P, a carbon tax rate, τ, technology, A, labor supply, L^s, and growth rates of technology and labor supply, a decentralized competitive equilibrium consists of factor prices $\{w, r\}$ agents' decision rules, $\{c, a'\}$, firms' production plans, $\{E, K, L\}$, and transfers, T, such that the following holds:

1. Given prices, policies, and transfers, the agent maximizes equation (13) with respect to equation (14) and the nonnegativity constraints, $a \geq 0$, $c \geq 0$.
2. Firm demands for E, K, and L, satisfy

$$P(1+\tau) = \theta K^{\alpha} E^{\theta-1} (AL)^{1-\alpha-\theta}, \qquad r = \alpha K^{\alpha-1} E^{\theta} (AL)^{1-\alpha-\theta} - \delta, \quad \mathbf{(15)}$$

$$w = A(1-\alpha-\theta) K^{\alpha} E^{\theta} (AL)^{-\alpha-\theta}.$$

3. Transfers satisfy: $T = \tau P E$

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4. Market clearing:

$$L^s = L \quad (16)$$

$$a = K \quad (17)$$

$$Y + (1 - \delta)K = K' + C + PE \quad (18)$$

3.3. Calibration

I perform an illustrative calibration to demonstrate the dynamic welfare implications of the upper bound on the energy intensity of capital for climate policy. The model has eight parameters to be determined: $\{\alpha, \beta, \delta, P, \sigma, \theta, AL, X\}$. I calibrate these parameters from U.S. data on capital, fossil energy consumption, and energy prices. Data on fossil energy use and prices are from the Energy Information Administration. All other data are from the Bureau of Economic Analysis. The time period is one year.

3.3.1. Preferences. I determine β to match the U.S. capital–output ratio of 2.7 in an economy at its long-run steady state. This yields $\beta = 0.98$. I use the standard value of 0.5 for the intertemporal elasticity of substitution, $\frac{1}{\sigma} = 0.5$.

3.3.2. Production. Following Golosov et al. (2014), the value of capital's share is $\alpha = 0.3$ and of energy's share is $\theta = 0.04$. I determine the depreciation rate, δ, to match the U.S. investment–output ratio of 0.255 in an economy at its long-run steady state. This yields $\delta = 0.064$. I set the exogenous growth rate of AL equal to the average annual growth rate of U.S. gross domestic product (GDP) in the National Income and Product Accounts from 1949 to 2011. This choice implies that countries on the long-run balanced growth path grow at 3 percent per year. I normalize the level of AL to unity in the first period.

I calibrate the relative price of fossil energy to match the energy intensity of capital for a developed country in its long-run steady state. A developed country's optimal energy intensity is given by equation (5) with $\lambda = 0$. Using this expression for optimal energy intensity, the value of the steady state capital–labor ratio in the model, and data on the energy intensity of U.S. capital, I find that the relative price of fossil energy, P, equals 0.01 million (2014) dollars per billion BTUs.[7] This price calibration is consistent with measures of the composite energy price equal to an average of the prices of coal, natural gas, and petroleum weighted by the relative quantities of each fuel consumed in a given year.

3.3.3. Upper bound on energy intensity. I do not calibrate a value for the upper bound on energy intensity, X. Instead, I consider a range of values equal to 1.5, 2, 2.5, and 3 times the average energy intensity of U.S. capital over the past ten years, 2003–2013. This yields $X = \{2.3, 3.1, 3.8, 4.6\}$ billion BTUs per million (2014) dollars of capital. I set $X = 2.3$ in the main specification. Table 1 reports the calibrated parameter values.

TABLE 1. Calibrated parameters

Parameter	Value	Target
Production		
Capital share: α	0.3	Golosov et al. (2014)
Energy share: θ	0.04	Golosov et al. (2014)
Energy price: P	0.01	Data
Annual growth rate of AL	0.03	Data
Depreciation: δ	0.064	$\frac{I}{Y} = 0.25$
Upper bound: X	$\{2.3, 3.1, 3.8, 4.6\}$	Illustration
Preferences		
Discount factor: β	0.98	$\frac{K}{Y} = 2.7$
IES: σ	0.5	Standard

3.3.4. Quantifying the level of development. The calibrated parameter values are the same for all countries. Thus, there is a single balanced growth path and a single steady-state capital-labor ratio. I define a country as developed if its capital–labor ratio is near the steady-state value and developing if its capital–labor ratio is far from the steady-state value. The model calibration implies that developed countries grow at 3 percent per year along the balanced growth path. However, developing economies will grow faster than 3 percent per year as they transition to the long-run balanced growth path.[8]

3.4. Dynamic Results

3.4.1. Uniform carbon tax and uniform abatement target. I perform three dynamic simulations: (1) a baseline economy with no carbon tax, (2) a constant, uniform carbon tax, and (3) a constant, uniform abatement (quantity) target. In the baseline, I simulate the country's aggregate consumption, saving, and energy decisions over time, in the absence of climate policy. I compute this baseline using a range of capital–labor ratios as starting points to obtain lifetime welfare estimates for countries beginning at different stages of economic development.

In the carbon tax simulation, I introduce a constant carbon tax equal to 35 dollars per ton CO_2, approximately 32 percent of the energy price. I simulate the country's capital and energy decisions over time under the tax. I compute this policy experiment using a range of capital–labor ratios as starting points to calculate the effects of the policy for countries that introduce the tax at different stages of economic development. When a country's capital–labor ratio is past the threshold, this size tax results in 25.7 percent reduction in emissions.

In the abatement target simulation, I set the target equal to 25.7 percent to facilitate the comparison between the abatement target and carbon tax. To implement this target, I impose a carbon tax that varies with the capital-labor ratio and hence changes over time as the country develops. This design is similar to the way in which the carbon permit price changes to ensure a constant quantity of abatement

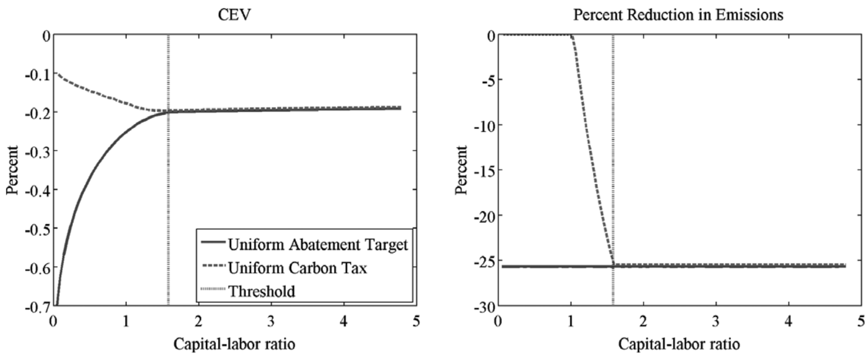

FIGURE 2. Welfare and abatement effects of the uniform tax and the uniform target.

in a cap-and-trade system. Specifically, for each value of the capital–labor ratio, I choose the size of the tax such that energy use by a firm with that capital–labor ratio is 25.7 percent below the energy use by a firm with the same capital–labor ratio and no carbon tax. Again, I compute this policy experiment using a range of capital–labor ratios as starting points. In all three simulations, I set the upper bound on energy intensity equal to 2.3 (1.5 times the U.S. energy intensity of capital).[9]

To measure the welfare costs of each policy, I calculate the consumption equivalent variation (CEV). I define the CEV as the uniform percent change in consumption the agent would need in every period of the baseline such that he is indifferent between the baseline and the policy. A positive value for the CEV indicates that the policy makes the country better off relative to the baseline, whereas a negative value indicates that the policy makes the country worse off. This measure of welfare only includes the welfare cost of the climate policy; I do not model the climate benefits from the reduced emissions.

The left panel of Figure 2 compares the welfare costs of the uniform carbon tax and the uniform abatement target. The panel plots the CEV of each policy on the vertical axis as a function of the country's level of development in the year the policy is introduced on the horizontal axis. For example, the CEV for a capital–labor ratio equal to 2, measures the effect of the climate policy on lifetime welfare for a country that implements the policy when its capital–labor ratio equals 2 and then grows over time as a result of its endogenous savings decisions. The welfare consequences of the carbon tax are the same as for the abatement target in countries that implement the policy when they are past the before-tax threshold, $\Omega(0)$. However, the welfare costs of the uniform abatement target are substantially higher than the corresponding costs of the uniform carbon tax for countries that introduce the policy before they reach $\Omega(0)$.

The welfare costs under each policy are determined by the policy's effect on abatement. The right panel of Figure 2 compares the effect of each policy on abatement. Specifically, the panel plots the annual percent reduction in emissions from the policy on the vertical axis as a function of the current period capital–labor ratio on the horizontal axis. For example, the percent reduction in emissions in the current period, for a country whose current-period capital–labor ratio equals 2 (above the threshold), is along the horizontal line at 25.7 percent. If, five years ago, this country had a capital–labor ratio of 1 (below the threshold), then its emission reduction under the carbon tax would have been zero in that period.

Beyond the threshold, the level of abatement is the same under both policies, and, thus, the policies have identical welfare consequences for countries that implement them when their development levels exceed the threshold. However, before the threshold, the uniform carbon tax implies substantially less emissions reduction than the uniform abatement target, and, thus, the welfare costs are lower under the uniform carbon tax.

In countries that have not reached the threshold, the uniform carbon tax does not incentivize firms to reduce emissions because the upper bound binds in these countries. Thus, the tax does not lead to changes in behavior until these countries develop past the threshold. These dynamics imply that the welfare cost of the tax does not realize until the future for these countries (i.e., until they pass the threshold), reducing the lifetime welfare cost under the carbon tax.

In contrast to the uniform carbon tax, the uniform abatement target requires the country to reduce energy intensity from its observed level, regardless of its stage of development. Hence, the percentage reduction in emissions under the uniform abatement target is the same for all values of the capital–labor ratio. However, the welfare cost of this reduction in emissions is much larger for developing countries whose capital–labor ratios are below the threshold when they implement the policy. When a country is below the threshold, the upper bound already forces the country to reduce its energy intensity from its *unconstrained* optimum (i.e., the optimal level of energy intensity if there was not an upper bound). Since the abatement target is measured as a percentage reduction in emissions from the country's observed energy intensity, not from its unconstrained optimum, the target results in a larger percentage reduction in emissions from the unconstrained optimum when the country is below the threshold.

As a result of this discrepancy, larger carbon taxes are required to achieve the uniform abatement target in countries that have not reached the threshold. Figure 3 plots the carbon tax necessary to attain the uniform abatement target as a function of the capital–labor ratio. As discussed in Section 2.3, the tax must first move the firm from the corner to the interior and then incentivize the necessary reduction in emissions. The larger carbon taxes in countries below the threshold imply that the uniform abatement target creates substantially larger distortions in these developing economies. As a result, the welfare cost of achieving the target is larger for developing countries who introduce the uniform abatement target when their capital–labor ratios are below the threshold.

The notion of fairness across countries has been a key issue in many recent climate negotiations. These results suggest that neither a uniform carbon tax nor a uniform abatement target is "fair" in the sense that it equalizes the welfare costs across countries. Instead, if policy makers strive to equalize welfare costs, then

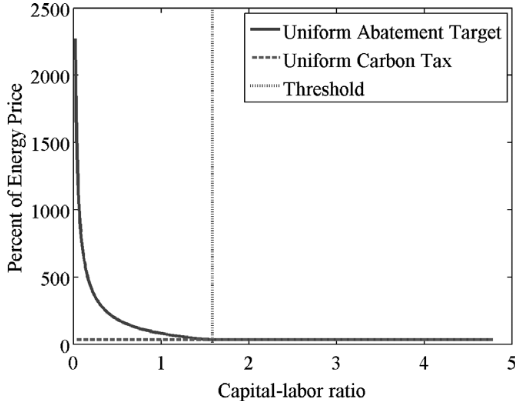

FIGURE 3. Size of the carbon tax.

TABLE 2. Empirical values of the capital-labor ratio

Country	Ratio
Brazil	2.22
China	2.32
India	0.68
Indonesia	1.16
Mexico	1.77
United States	4.34

TABLE 3. Capital–labor thresholds for different upper bounds

	$X = 1.5 \times \left(\frac{E}{K}\right)_{\text{US}}$	$X = 2 \times \left(\frac{E}{K}\right)_{\text{US}}$	$X = 2.5 \times \left(\frac{E}{K}\right)_{\text{US}}$	$X = 3 \times \left(\frac{E}{K}\right)_{\text{US}}$
Threshold: $\Omega(0)$	2.4	1.6	1.1	0.9

they should either assign developing countries higher carbon-tax rates or lower abatement targets.

3.4.2. Application: Developing countries and the threshold. I analyze the implications of the above results for some of the world's largest, developing-country, carbon emitters: Brazil, China, India, Indonesia, and Mexico. Table 2 reports the capital–labor ratios, $\frac{K}{AL}$, in each of these countries and in the U.S. based on 2011 data on capital, labor, and total factor productivity from the Penn World Tables [Feenstra et al. (2013)].

As discussed in the preceding sections, the upper bound on energy intensity leads to a threshold capital–labor ratio. The effects of climate policy are different

Table 4. Welfare-equivalent carbon taxes: Percent difference from $35 per ton

	Threshold			
Country	$\Omega = 2.4$	$\Omega = 1.6$	$\Omega = 1.1$	$\Omega = 0.9$
Brazil	0.4	0	0	0
China	0.4	0	0	0
India	25.0	12.5	3.1	0.2
Indonesia	12.5	1.6	0	0
Mexico	3.1	0	0	0

for countries above and below this threshold. Table 3 reports these thresholds for different values of the upper bound on energy intensity. I consider upper bounds equal to 1.5, 2, 2.5, and 3 times the average U.S. energy intensity of capital from 2003 to 2013.

Comparing the results in Tables 2 and 3, if the upper bound is relatively tight, equal to 1.5 times the U.S. energy intensity of capital, then all the countries in Table 2 except the U.S. are below the threshold. This result suggests that uniform abatement targets would be considerably more costly in these countries than in developed countries like the U.S. and the E.U. Moreover, a uniform carbon tax would be considerably less costly in these countries, but it would also attain a smaller percentage reduction in emissions.

If the upper bound is less tight, equal to two times the U.S. energy intensity of capital, then Brazil, China, and Mexico are all above the threshold. In contrast, India's capital–labor ratio is so small that the upper bound would have to exceed three times the U.S. energy intensity of capital for India to be above the threshold.

To address issues of cross-country fairness, I calculate the constant carbon tax for each country that incurs the same welfare cost as a 35 dollar per ton tax in the U.S. Table 4 reports the percent difference in these "welfare-equivalent" taxes from the U.S. tax of 35 dollars per ton. Equal welfare costs require larger carbon taxes in developing countries below the threshold because the policy does not lead to substantial changes in firm behavior until the country develops past the threshold. For example, for $\Omega = 2.4$, the results in Table 4 imply that the carbon tax in India needs to be 25 percent larger than the U.S. value for India to incur the same welfare cost from the policy as the U.S. However, while the results indicate larger carbon taxes for developing countries below the threshold, the level of abatement could be lower. Even with the 25 percent larger carbon tax, India's level of development is still below the threshold in the near-term and hence the representative firm will not reduce emissions until it develops past the threshold. Thus, the welfare-equalizing policy is more strict in terms of the size of the carbon tax but more lenient in terms of the level of abatement for developing countries below the threshold.

4. GENERALIZATION: TECHNOLOGY AND ENERGY PRICES

Factor augmenting technical progress is exogenous. However, if technology is endogenous and innovation can be directed toward reductions in energy intensity, then a similar analysis could imply that there exists a technology threshold below which the firm does not invest innovation resources in technology that reduces energy intensity. This additional threshold would further support the result that uniform abatement targets are more distortionary in developing countries with capital–labor ratios below a threshold value.

The price of fossil energy is exogenous and, thus, I abstract from the general equilibrium effects of a carbon tax on energy prices. If energy prices are endogenous, then a carbon tax should reduce the before-tax energy price, since it reduces the demand for fossil energy. This effect implies a smaller after-tax energy price. The change in the threshold from the carbon tax is increasing in the magnitude of the change in the after-tax energy prices. Therefore, the tax-induced fall in the threshold with exogenous energy prices is an upper bound on the magnitude of the fall in the threshold when energy prices are endogenous.

5. CONCLUSION

This paper develops a macroeconomic model in which firms choose capital, labor, and fossil energy to maximize profits subject to an upper bound on the energy intensity of capital. There are three key results. First, a firm's incentives to economize on energy use are inversely related to the relative price of capital. Capital prices are typically higher in developing countries, implying that developing countries optimally choose to use more energy per unit of capital than their developed counterparts. Hence, the upper bound on the energy intensity of capital is more likely to bind in developing countries. This result suggests that the elasticity of energy demand is likely to be smaller in developing countries.

Second, the relative welfare costs of the uniform carbon tax are smaller in developing countries below the threshold, whereas the welfare costs of the uniform abatement target are larger. The uniform carbon tax leads to smaller near-term distortions in behavior for countries below the threshold, reducing both the effectiveness (in terms of emissions reduction) and welfare cost of the policy. In contrast, the abatement target forces policy makers in countries below the threshold to amplify the existing distortion to energy intensity created by the upper bound, substantially raising the welfare cost of the policy.

Third, the calibration implies that for most plausible values of the upper bound, the constraints on energy intensity bind in India but not in China. Therefore, the model suggests that the welfare cost of a uniform abatement target would be considerably larger in India, whereas the welfare cost of uniform carbon tax would be considerably smaller. Moreover, a carbon tax policy designed to equalize welfare costs across countries would require a substantially larger carbon tax in India than in China or the U.S.

This paper demonstrates that inappropriate technology in developing countries can generate substantial spatial variance in the welfare cost and effectiveness of climate policy. A promising direction for future research is to explore how to construct measures of inappropriate technology and incorporate them into a more detailed microsimulation model.

NOTES

1. Throughout the paper, I use the term welfare cost to refer to the welfare cost of the policy relative to the baseline market outcome with no policy in place.
2. This paper does not address the question of optimal policy and instead analyzes alternative policy reforms to reduce emissions. Additionally, this paper focuses solely on the welfare costs of climate policy and omits the welfare benefits from climate improvements.
3. At any point in time, a country's stocks of capital and labor are fixed. Although the representative firm optimally chooses capital and labor, the general equilibrium forces cause the wage and the rental rate to adjust to ensure that the country's capital stock is fully utilized and the labor force is fully employed.
4. Copeland and Taylor (1994) and Stokey (1998) use a related production function with an upper bound on the pollution intensity of output to explain the environmental Kuznets curve.
5. Consistent with this extreme nonsubstitutability, Hassler et al. (2012) estimate that the elasticity of substitution between a Cobb–Douglas capital–labor composite and energy equals 0.04.
6. Note that I assume that the country behaves as a closed economy with respect to capital. This assumption generates smaller capital–labor ratios in developing countries, consistent with the empirical evidence and the Feldstein and Horioka (1980) stylized fact that savings and investment are highly correlated within a country.
7. Specifically, I use the average energy intensity of U.S. capital over the past ten years (2003–2013), which equals 1.53 billion BTUs per million (2014) dollars.
8. Additionally, note that the climate policy can impact the rate of development (through its effects on capital accumulation) and, hence, affect the rate of growth for countries who have not yet reached the balanced growth path.
9. Note that while the carbon tax varies with the aggregate capital–labor ratio, the individual firm takes the tax as given when it makes its capital and labor decisions. The effects of one firm's decisions on the aggregate are tiny.

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APPENDIX

A frequent critique of the Cobb–Douglas specification is the substitutability between capital and energy. After all, more capital in the form of buildings and machines requires more energy, not less. In this appendix, I show that the Cobb–Douglas production structure with an upper bound on energy intensity can be equivalent to a production function that directly models the substitutability between capital and fossil energy, through improved fossil efficiency.

Consider the following production structure. The representative firm combines capital, labor, and fossil energy to maximize profits. In each period, the firm divides its total capital stock, K, between a productive and a green use. Productive capital is used to generate output. Green capital reduces the firm's fossil energy expenses by increasing its fossil efficiency. Increases in fossil efficiency include both improving the energy efficiency of machines (i.e., cars with better fuel economy) and fuel switching (i.e., using wind turbines instead of coal to produce electricity). Let g be the fraction of total capital that is green.

For a given amount of green capital, firm production is Leontief in a productive-capital-labor composite and fossil energy. There are two exogenous types of technological progress: factor augmenting technological progress, A, and a fossil-energy saving or "green" technological progress, A_g. This production function is analogous to the one estimated in Hassler et al. (2012) with the addition of green capital. The functional form is

$$Y = \min\left[A((1-g)K)^{\alpha}L^{1-\alpha},\ \left(\frac{A((1-g)K)^{\alpha}L^{1-\alpha}}{\Theta(g,K)}\right)A_g E\right].$$

Equating the two arguments of the min function and solving for E implies that the total fossil energy required to produce $A((1-g)K)^{\alpha}L^{1-\alpha}$ units of output is $\frac{\Theta(\cdot)}{A_g}$. This fossil energy requirement is endogenously determined by the firm's investments in green and productive capital and exogenously determined by green technological progress. I refer to $\Theta(g, K)$ as the energy requirement function.

The functional form for the energy requirement should satisfy three conditions to capture the key features of energy use. First, the energy requirement should be increasing in productive capital and decreasing in green capital. Second, there should be diminishing returns to green capital, implying increasing marginal costs of emissions abatement. Third, the energy requirement should be homogeneous of degree one in K. This homogeneity implies that if the total capital stock doubles and the fractions of productive and green capital are unchanged, then fossil energy use will double. A simple functional form that satisfies these three conditions is $\Theta(g, K) = K(1-g)^{1+\phi}$.

Given this functional form for the energy requirement, the energy intensity of productive capital is

$$\frac{E}{(1-g)K} = \frac{(1-g)^{\phi}}{A_g}. \tag{A.1}$$

Higher levels of green capital reduce the energy intensity of capital, reducing the energy requirement. The endogenous energy requirement explicitly models the substitutability between productive capital and energy through investment in green capital.

The optimization problem for the firm with this production structure is

$$\max_{K,g,L} \{A[(1-g)K]^{\alpha} L^{1-\alpha} - P(1+\tau)E - RK - wL\}, \tag{A.2}$$

$$\text{where } E = \frac{\Theta(g, K)}{A_g} = \frac{K(1-g)^{1+\phi}}{A_g}, \tag{A.3}$$

and subject to the constraint

$$0 \le g \le 1. \tag{A.4}$$

This formulation is equivalent to the Cobb–Douglas production function with an upper bound on energy intensity. To see this, first solve equation (A.3) for $1-g$:

$$1 - g = \left(\frac{E}{K} A_g\right)^{\frac{1}{1+\phi}}. \tag{A.5}$$

Then, substitute equation (A.5) into the constraint [equation (A.4)] to obtain

$$0 \le \frac{E}{K} \le \frac{1}{A_g}. \tag{A.6}$$

Finally, substituting equation (A.3) directly into the the firm maximization problem [equation (A.2)] and using the constraint in equation (A.6) yields

$$\max_{E,K,L} A A_g^{\frac{\alpha}{1+\phi}} E^{\frac{\alpha}{1+\phi}} K^{\alpha - \frac{\alpha}{1+\phi}} L^{1-\alpha} - P(1+\tau)E - RK - wL$$

subject to

$$\frac{E}{K} \le \frac{1}{A_g}. \tag{A.7}$$

This optimization problem is isomorphic to the production function and upper bound introduced in Section 2.

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