The Political Economy of Embodied Technologies

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The presumption of this paper is that some governments value the environment, but others do not. Assuming political uncertainty and capital-intensive technologies, this circumstance yields a political economic process that emphasizes the effect of using current policy to influence future outcomes. The result of the analysis suggests that the optimal dynamic tax is larger than the Pigovian tax and that a standard results in more employment and output and yields higher adoption rates, thus achieving a predetermined pollution target with a lower political economic cost than a tax – with policy outcomes being more resilient to political change.

JEL code: L5, O2, O3, Q2, Q3

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I. Introduction

A large body of political science literature on Western democracies documents the great diversity in the list of values and actions supported by various political parties and individual candidates (Gunther & Diamond, 2003) – diversity that results in policy changing over time. However, can choice of policy instruments affect policy's long-term outcomes, resulting in incumbent governments leaving a legacy attributed to the policy they ushered in? While focusing on a subset of policies that address externalities and lead to the replacement of dirty technologies with clean ones, this work compares the long-term impact of two policy instruments: a tax and a standard.

The literature on the selection of environmental policies is extensive, starting with Pigou (1932) and later expanded by Baumol and Oates (1971), Weitzman (1974), Buchanan and Tullock (1975), and Laffont and Tirole (1996a, 1996b), among many others. This literature usually emphasizes efficiency while taking a welfare economic perspective. To correct the pollution externality, the literature usually recommends the use of a tax to provide incentives for polluters to reduce pollution. The literature generally expresses a critical view of forcing technological change and questions the effectiveness of command-and-control policies (Jaffe et al., 2002; Bansal & Gangopadhyay, 2005), arguing that firms are often unclear about the cost of compliance (Miller, 1995; Kemp, 1997; Gerard & Lave, 2005) and that regulators' ability to enforce regulations is questionable (Lutz et al., 2000; Bansal & Gangopadhyay, 2005; Gerard & Lave, 2005; Mohr, 2006; Puller, 2006; Mickwitz et al., 2008). Although the literature has criticized the use of policies mandating that firms go beyond the existing technological capabilities of their industry and force technological change, such policies have numerous success stories, including the development of substitutes for chlorofluorocarbons (Ashford et al., 1985; McFarland, 1992), the development of flue gas desulfurization systems for SO2 control in the power sector (Popp, 2003; Taylor et al., 2005), and the control of automobile emissions (Jaegul et al., 2010), among many other examples. While much of the literature takes a welfare economic perspective, we approach the problem from a political economic vantage point.

The political economic literature recognizes the limitations of governments' survival over time and thus the challenge of enacting policies that will not be overruled in the longer run. To address such issues, the study of public policy problems that pertain to the long run has evolved into two strands of literature: (a) the inefficiencies associated with political opportunity costs that draw on the differences between the objectives of politicians and those of voters (e.g., Persson & Tabellini, 1999; Acemoglu & Robinson, 2001; Grossman & Helpman, 2001; Bohn, 2007; Rausser et al., 2011) and (b) politicians' incentive to manipulate current policy and influence both future elections and policy choices of future governments (e.g., Persson & Svensson, 1989; Aghion & Bolton, 1990; Tabellini & Alesina, 1990; Persson & Tabellini, 2000; Azzimonti, 2011; Millner et al., 2013). While building on the second body of literature, this paper investigates the impact of political uncertainty with respect to future governments on the choice of environmental policy instruments, assuming some parties place more weight on the environment than others.

This paper presents a political economic framework of a model for the selection of policy tools in the context of a choice of environmental policy. This framework will provide a new perspective to the literature that aims to explain the use of financial incentives versus direct control policies to address externality problems. The model developed is a two-period model that aims to capture a dynamic feature of political decision making, namely, the transition among ruling parties. The model is based on the presumptions that (i) policy makers at the present aim to design policy outcomes that will survive a political transition and (ii) production units employ a capital-intensive technology that consists of several activities, each with its own fixed proportion properties (i.e., a putty-clay technology). The empirical literature has shown that these technologies – the putty-clay technologies whereby the production coefficients are fixed in the short run – fit well the energy sector (Dasgupta, 1970; Fuss, 1978).

We model a political economic process that emphasizes the effect of using current policy to influence future outcomes. We assumed an industry that relies on capital-intensive technologies and that regulation leads to modifications of the fixed capital-intensive assets and the adoption of clean technologies. However, because of political uncertainty, the party that places more weight on the environment sets an optimal dynamic tax that is larger than the Pigovian tax that simply maximizes the social welfare over time.

Using a static framework and assuming a predetermined aggregate pollution level, Hochman and Zilberman (1978) demonstrated that a standard results in more employment and higher output than a tax. Caparros et al. (2015) used a dynamic putty-clay framework to compare the performance of pollution taxes and upper bound regulation on pollution. The framework presented here shows that an upper bound on pollution intensity results in a higher level of output and, more importantly, greater adoption of clean technologies. Our numerical analysis suggests that, given a predetermined aggregate pollution level, a standard influences the rate of adoption much more than a tax but that a tax results in more production units exiting and becoming idle. The standard leads to higher adoption rates in the short run and thus makes reversing policy outcomes harder.

However, although environmental policy influences future outcomes by altering the embodied technology employed in the industry, policy is time-inconsistent. The optimal policy calculated at time zero will not be optimal in future periods when the policy is reevaluated (Fischer, 1980). That is, a fixed policy is inferior to a dynamic policy that changes over time. The dynamic inconsistency occurs even though the government maximizes its political economic objectives at time zero. These results are similar to those presented in the macro literature (Kydland & Prescott, 1977; Calvo, 1978).

With embodied technologies, environmental policy yields changes that are more stable over time. The Clean Air Act of 1970 allowed the U.S. Environmental Protection Agency (EPA) to regulate motor vehicle pollution, with the first-generation catalytic converters in 1975 significantly reducing hydrocarbon and carbon monoxide emissions. A major milestone in vehicle emission control technology came in 1980-1981 in response to standards becoming tighter over time. This technological change included emission control systems that optimized the efficiency of the catalytic converter. The 1990 Clean Air Act included even tighter tailpipe standards and was followed with manufacturers increasing the durability, control of evaporative emissions, and computerized diagnostic systems that identify malfunctioning emission controls. However, standards have also promoted more controversial technologies, and some have expressed concern about the ramifications of choosing technologies as opposed to letting the market find the solution. For example, Germany’s Renewable Energy Act led to prosperous wind, solar, and anaerobic digester industries. Although several governments have come to power since enactment of this act, and some have viewed the development of wind and solar industries as a waste of taxpayers’ money, these industries continue to thrive. Another example of a controversial environmental policy mandating a change that resulted in an economically viable industry in the U.S. is the Renewable Fuel Standards of

2005, which was revised in 2007, and led to the development of a flourishing corn-ethanol industry.

The paper proceeds as follows. The conceptual model is introduced in section 2. Section 3 describes the two-period game. The analysis begins in section 4, where the tax equilibrium is derived. We switch to a pollution-intensity upper bound in section 5 and compare the outcome of a tax to the outcome of an intensity upper bound in section 6, where we also calculate the effect of policy on adoption. General policy discussion and concluding remarks are presented in section 7.

II. The Conceptual Model

We assume a fixed coefficients production function in the short run that are the outcome of past decisions.. In each moment, a production unit faces two alternatives: (i) to keep the existing technology, or (ii) to adopt a new technology with a different set of coefficients. This process yields technical coefficients that are continuously modified over time by the choice of the technology. Assuming many production-units face these alternatives, results in a different set of initial coefficients at each point in time. This modeling is consistent with the empirical literature that estimates the adoption of discrete technologies and evaluates technological change.

Both Fuss (1978) and Dasgupta (1970) suggested that the putty-clay approach fits the energy sector well, and several studies assessed the impact of energy regulation using the putty-clay specifications (see survey by Khanna and Rao, 2009). Moffitt et al. (1978) applied the putty-clay approach to analyze waste-management regulation, and Sunding and Zilberman (2002) used the putty-clay framework to assess the impact of water market reforms in California.

Furthermore, studies by Paris (1992) and Berck and Helfand (1990), among others, showed that the fixed proportion Von-Liebig production function fits well agricultural production systems, thus justifying, for example, the approach taken by Babcock et al. (1997) and Wu et al. (2001) who used putty-clay specifications to assess various payments for ecological service schemes. These and other empirical studies confirm the insight of Houthakker (1955) and Johansen (1972), who showed that the putty-clay approach results in aggregate production functions that are well behaved and simple to construct and analyze.

Formally, we assume a production function of fixed proportions and constant input prices. Also assume a one-variable input that can be measured in monetary terms that capture the costs per output unit and normalize the price of the input to 1. Production also generates pollutants in a fixed proportion. Formally, let $x \in (0, \bar{x})$ denote the fixed input-output coefficient and $\beta \in (0, \bar{\beta})$ the fixed pollution-output coefficient. A lower x denotes a more cost-efficient production unit and a higher β denotes the more pollution-intensive units. While the model can be more complex to include changes in output and other inputs, among other modifications, for brevity and simplicity, this basic model suffices.

Assume a production unit produces one unit or is idle. Define the production unit current-period quasi-rents π^0 as

$$\pi^0 \equiv p - x, \tag{1}$$

where p denotes output price. The production unit then chooses either to become idle and not produce (i.e., $\pi^0 < 0$) or remain active, earn non-negative quasi-rents, and produce at capacity (i.e., $\pi^0 \geq 0$).

The production unit may also make irreversible investments, thus modifying its technology. Irreversible investment means that an investment cannot be fully recovered once installed and this irreversibility limits a production unit's ability to redeploy capital. Although it is sufficient to assume that production units cannot change technologies without costs, we chose the stronger assumption that simply disallowed the redeployment of capital because it made the presentation clearer and simpler.

Technically, assume that investment decisions are discrete choices and that a production unit may invest $\mathrm{I}_{\mathrm{t}}^{\mathrm{m}} > 0$ and modify its existing technology via adopting the cleaner technology. Let superscript m denote the modified technology, let subscript $t = \{1,2\}$ denote period t, and assume the modified technology reduces emissions by $\gamma \geq 0$. The production unit may invest $I_1^m > 0$ in period 1 and modify its pollution-intensity coefficient, that is, $\beta^m = (1-\gamma) \cdot \beta$. However, the new technology may also affect the input-output coefficient. Let $\rho \geq 0$ denote the effect of the adopted technology on production costs and assume $x^m = (1+\rho) \cdot x$. These assumptions capture the idea that while the average annual fuel cost of generating one-megawatt hour using fossil steam is \$3.73 U.S., it is \$6.71 U.S. using hydroelectricity – that is, it is cheaper to produce one-megawatt hour using the polluting technologies than the cleaner ones.[1]

Improvement in productivity is obtained via practice, self-improvements, and small innovations (Arrow, 1962). Recent studies on adoption of renewable technologies, however, have argued that the negative correlation between cost and capacity is tenuous (Nordhaus, 2009). We do not aim to contribute to this debate and simply assume that the cost of adopting a technology declines with time. Specifically, we assume adoption of second-period technology requires less

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[1] Data are available at http://www.eia.gov/electricity/annual/html/epa_08_04.html (viewed February 18, 2014).

upfront capital and does not affect production costs. Formally, we assume $I_2^m = (1-\omega)I_1^m$ where $\omega > 0$ and adopting clean technology in the second period does not change the per-unit production costs, that is, $\rho = 0$. For simplicity, we also assume that $\gamma_2 = \gamma_1 (\equiv \gamma)$.

To derive the aggregate supply of output, denoted by Y, we follow Hochman and Zilberman (1978) – who followed Johansen (1972) – and define an output capacity distribution function $g(\beta, x)$. The output capacity of production units located in the set $(\beta, \beta + d\beta)\times(x, x + dx)$ for small $d\beta$ and dx are simply $g(\beta, x)d\beta dx$. We assume that $g(\beta, x)$ is a smooth function with compact support. This output-capacity distribution function is used to define the output produced by units located in region $R \subseteq \left(0, \bar{\beta}\right)\times(0, \bar{x})$, that is, $Y^0 \equiv \int\int_R g\,(\beta, x)d\beta dx$.

We now transition from the individual production unit to the aggregate industry level and define the survival region. Let R^0 denote the survival region in the $\beta - x$ space, formally defined as follows:

$$R^0 \equiv R(p) = \left\{(\beta, x) \mid 0 \le \beta \le \bar{\beta}, 0 \le x \le p\right\},$$

assuming $p < \bar{x}$. Put differently, production units $R - R^0 \equiv \left\{(\beta, x) \mid 0 \le \beta \le \bar{\beta}, p < x \le \bar{x}\right\}$ remain idle.

The industry generates aggregate output supplied, aggregate pollution demanded, and aggregate input demanded, respectively, as follows:

$$Y^0 \equiv \int\int_{R^0} g\,(\beta, x)d\beta dx, \qquad (2)$$

$$Z^0 \equiv \int\int_{R^0} \beta \cdot g(\beta, x) d\beta dx, \text{ and}$$

$$X^0 \equiv \int\int_{R^0} x \cdot g(\beta, x) d\beta dx.$$

Assume a downward-sloping demand function $\mathrm{Q} = \mathrm{D(p)}$, $\partial \mathrm{D(p)}/\partial \mathrm{p} < 0$. Then, the equilibrium price is determined by $\mathrm{Y}^0 = \mathrm{Q}$. At this equilibrium price (p^0), the marginal firm earns zero quasi-rents (i.e., $\mathrm{x} = \mathrm{p}^0$). Then, assuming pollution does not affect consumers' benefit from the good consumed, consumer surplus (CS) and producer surplus (PS) are, respectively,

$$\begin{gathered} CS^0 = \int_{p^0}^{\infty} D\,(p) dp \\ PS^0 = p^0 \cdot Y^0 - X^0 \end{gathered} \tag{3}$$

The industry generates a flow of pollution, and this flow generates a stock of pollution. Let $\mathbb{Z}_t = Z_{t-1}(1 - \Psi) + Z_t$ denote the pollution stock in period t, where the flow of pollution in period t is Z_t and where Ψ is the pollution-decay parameter. Note that if $\Psi = 1$, then only current-period pollution matters. For simplicity, we normalize the initial stock of pollution to 0; thus, $\mathbb{Z}_1 = Z_1$. In addition, we assume that policy makers know the period t social cost of pollution, $C(\mathbb{Z}_t) = \xi \cdot \mathbb{Z}_t^2$ for $\xi \quad 0$.

Finally, we define social welfare assuming separability between economic activities and environmental amenities, and assume that period t social welfare is

$$W_t = CS_t + PS_t - C(\mathbb{Z}_t). \tag{4}$$

III. The Two-Party Two-Period Game

We wanted to assess the implications of the presupposition of uncertainty with respect to future governments and to better understand the incumbent governments' strategic incentives to manipulate policy and tie the hands of future governments. Thus, and to maintain clarity, we assume a two-party system (i.e., Party A and Party B) and a two-period game. Furthermore, although in the first period Party A is in power, we assume a random draw determines which party will be in power in period 2; that is, with probability $\alpha \in (0,1)$, Party A is in power in the second period, but with probability $(1-\alpha)$, Party B is in power in the second period. We also assume that Party A strives to maximize social welfare, but Party B places no weight on the environment.

Formally, let $V_{A,t}$ denote Party A's objective function and $V_{B,t}$ denote Party B's objective function, where subscript $t \in \{1,2\}$ denotes period *t*. Also, let δ denote the discount rate and $W_{j,t}$ the social welfare of period *t* when Party *j* is in power.

The first period starts with Party A in power. Party A chooses policy to maximize $V_{A,1}$:

$$V_{A,1} \equiv W_{A,1} + \delta\big(\alpha W_{A,2} + (1-\alpha)W_{B,2}\big). \tag{5}$$

Let $\varrho_{A,1}$ denote the policy that maximizes Eq. (5). Given policy $\varrho_{A,1}$, production units decide whether to remain active and whether to adopt the clean technology. These decisions define the first-period survival region. Then, given the policy-modified survival region, current-period profits and welfare materialize.

At the beginning of the second period, a random draw transitions the political system to the second period. If this results in Party A staying in power (i.e., Party A is reelected), then the second-period policy maximizes $V_{A,2}$:

$$V_{A,2} \equiv W_{A,2} = CS_{A,2} + PS_{A,2} - C(\mathbb{Z}_{A,2}). \tag{6}$$

Let $\varrho_{A,2}$ denote the policy that maximizes (6). However, if the random draw results in Party B being in power, then policy is set to maximize the sum of consumer and producer surplus, $V_{B,2} = CS_{B,2} + PS_{B,2}$. Once the ruling government sets policy, previously active units decide whether to remain active and active units that have not yet adopted the clean technology decide whether to adopt it. Then, second-period profits and welfare materialize.

This structure mimics, for instance, the response of U.S. power plants to the EPA's proposal to limit emissions of coal-fired plants to 1,100 pounds of CO_2 per megawatt hour. If such proposed regulation is enacted, then coal-fired power plants would either invest in cleaner technologies (e.g., natural gas-fired boilers, carbon storage and capture technologies, co-generation with biomass) or retire the plant. On the other hand, natural gas-fired plants continue to produce electricity using their existing technologies.

IV. The Optimal Dynamic Tax

Even though we assume competitive markets, the optimal tax may be larger than the dynamic Pigovian tax. To illustrate this, we modify Eq. (1) to include a tax τ, and let π_t^τ denote the period 1 expected quasi-rents, where units modified the technology in period *t*, $t \in \{1,2\}$, or never adopted the technology (i.e., π_0^τ):

$$\pi_1^\tau = P - (1+\delta)\cdot(1+\rho)\cdot x - I_1^m - (1-\gamma)\cdot T\cdot\beta \tag{7}$$

$$\pi_2^\tau = P - (1+\delta)\cdot x - \delta\cdot\alpha\cdot I_2^m - T\cdot\beta + \delta\cdot\alpha\cdot\tau_{A,2}\cdot\gamma\cdot\beta \tag{8}$$

$$\pi_0^\tau = P - (1+\delta)\cdot x - T\cdot\beta \tag{9}$$

We use Eqs. (7), (8), and (9) to define the first-period survival region (i.e., $R^{A,1}$), where $P \equiv p_{A,1} + \delta\{\alpha p_{A,2} + (1-\alpha)\cdot p_{B,2}\}$ and $\mathrm{T} \equiv \tau_{A,1} + \delta\cdot\alpha\cdot\tau_{A,2}$; that is,

$$R^{A,1} \equiv \{(\beta, x) \mid \{0 \le \pi_1^\tau\} \cup \{0 \le \pi_2^\tau\} \cup \{0 \le \pi_0^\tau\}, 0 \le \beta \le \bar{\beta}, 0 \le x \le p\}.$$

In addition, let $R^{m,1}$ denote the first-period modification region whereby units located in this region are active units that modified their technology in the first period. Production units located in region $R^{m,1}$ earn the highest quasi-rents when adopting the pollution abatement technology in the first period. These units are the dirtier yet efficient production units (see section 6.1). This suggests that if the EPA's proposal to regulate coal-fired power plants is enacted and results in a pollution tax on these plants, it will lead to inefficient coal plants shutting down, but the relatively efficient plants will shift to more environmentally benign technologies.

How does policy affect the survival and modification regions and thus aggregate pollution? Recall that the pollution-production coefficient of units that adopted the cleaner technology is $\beta^m = (1-\gamma)\beta$. Then, let $\Delta Z_1 = Z_1|_{\tau_1=0} - Z_1|_{\tau_1=\tau_{A,1}}$ denote the reduction of flow of pollution in period 1 (where $Z_1|_{\tau_1=0}$ denotes pollution assuming no regulation, and $Z_1|_{\tau_1=\tau_{A,1}}$ denotes pollution assuming first-period tax of $\tau_{A,1}$); that is,

$$\Delta Z_1 = \gamma\cdot\int\int_{R^{m,1}} \beta\cdot g(\beta, x)d\beta dx + \int\int_{R^0 - R^{A,1}} \beta\cdot g(\beta, x)d\beta dx.$$

Party A’s policy lowered pollution in the first period (i.e., $\Delta Z_1 > 0$); it reduced the number of active units and induced some active units to modify their technology and adopt cleaner technologies. However, policy enacted in the first period also affected the second period’s pollution stock; $\tau_{A,1}$ not only reduced the first-period stock of pollution yielding a decline of $(1-\Psi)\Delta Z_1$ in the second-period pollution stock, but first-period policy also permanently changed the technology employed by the industry. This suggests that environmental policy that yields changes to existing coal-powered plants will result in a permanent change to the pollution generated by the power sector, a change that will not be reversed if policy is revoked in the future (recall that investment is irreversible). Thus, we propose the following:

Proposition 1. *Given the aforementioned assumptions, the equilibrium policy choices made by governments are as follows:*

$$\tau_{A,1} = \big(2\xi\mathbb{Z}_{A,1} \quad \delta(1 \quad \Psi)\big(\alpha 2\xi\mathbb{Z}_{A,2} \quad (1 \quad \alpha)2\xi\mathbb{Z}_{B,2}\big) + \delta(1 \quad \alpha)2\xi\mathbb{Z}_{B,2}\big)$$

$$\tau_{A,2} = 2\xi\mathbb{Z}_{A,2}$$

$$\tau_{B,2} = 0$$

Proof: The proof is in Appendix A.

The optimal dynamic tax $\tau_{A,1}$ is the outcome of current-period pollution (*the static Pigovian tax effect*: $2\xi\mathbb{Z}_{A,1}$), pollution being a stock and thus affecting the next period (*the pollution stock effect:* $\delta(1 \quad \Psi)2\xi(\alpha\mathbb{Z}_{A,2} \quad (1 \quad \alpha)\mathbb{Z}_{B,2}))$ and uncertainty regarding the future (*the political uncertainty effect*: $\delta(1 \quad \alpha)2\xi\mathbb{Z}_{B,2}$). On the other hand, the Pigovian tax denoted ${\tau_{A,1}}^{Pigou}$ equals the difference between the marginal private cost and the social cost calculated at the optimal solution; that is, $\tau_{A,1}{}^{Pigou} \quad 2\xi\mathbb{Z}_{A,1}$ $\delta\big(1 \quad \Psi\big)\big(\alpha 2\xi\mathbb{Z}_{A,2} \quad \big(1 \quad \alpha\big)2\xi\mathbb{Z}_{B,2}\big)$. Proposition 1, then, leads to the following:

(a) Proposition 1 suggests that the dynamic Pigovian tax may not be the optimal tax from a political economic perspective, even when the number of producers and consumers is large.[2] Given political uncertainty (i.e., $\alpha < 1$) and $\delta > 0$, in equilibrium, Party A sets a higher pollution tax than the dynamic Pigovian tax; that is, $\tau_{\mathrm{A},1} > \tau_{A,1}{}^{Pigou}$.

(b) However, assuming no political uncertainty (i.e., $\alpha = 1$),

   i. The first-period tax equals the dynamic Pigovian tax; that is, $\tau_{\mathrm{A},1} = \tau_{A,1}{}^{Pigou}$.

   ii. In addition, if $\delta = 0$ and/or $\psi = 1$, then the first-period optimal tax is the static Pigovian tax; that is, $\tau_{\mathrm{A},1} = 2\xi\mathbb{Z}_{\mathrm{A},1}$.

When there is no uncertainty regarding future governments (i.e., $\alpha = 1$) and pollution is a flow, $\Psi = 1$, Party A has no incentive to diverge from the static Pigovian tax (bullet point (b.ii)). However, when $\Psi < 1$ and $\alpha = 1$, the optimal policy that maximizes social welfare is the dynamic Pigovian tax (bullet point (b.i)); that is, $\tau_{\mathrm{A},1} = 2\xi\mathbb{Z}_{\mathrm{A},1} + \delta\, 2\xi(1 - \Psi)\mathbb{Z}_{\mathrm{A},2}$. However, if political uncertainty exists (i.e., $\alpha < 1$), then Party A's optimal policy diverges from the dynamic Pigovian tax and, because investment is irreversible, Party A uses current policy to tie the hands of future governments and force larger changes in current period than suggested by the Pigovian tax (bullet point (a)).

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[2] Baumol and Oates (1988) showed that when the number of polluting units is small (i.e., one firm pollutes) or the damage is affecting a small number of consumers (i.e., the pollution is negatively affecting one firm), the Pigovian tax would not result in the optimal solution.

Because the game ends after the second period, period 2 tax is simply the Pigovian tax (i.e.,$\tau_{A,2}$= $2\xi\mathbb{Z}_{A,2}$). However, because Party B does not care about the environment, $\tau_{B,2} = 0$.

Politicians may elect not to choose a tax instrument because they care about the distributional implications of the regulatory system deployed. We explore the distributional implications of a standard and contrast them with a tax in section 6, but we first introduce the standard in section 5 and characterize its equilibrium outcome.

V. An Upper Bound on Pollution

Assume that a tax is not politically feasible, but that the government mandates an intensity upper bound (e.g., upper bound on chemical concentration of polluting elements in waste, air, and water, speed limits, and the California low carbon fuel standard). In the following paragraphs, we assess the efficacy of such a pollution restriction.

Technically, let $\theta_{j,i}$ denote the intensity upper bound set by Party j in period *i* for $j \in \{A, B\}$ and $i \in \{1,2\}$. We also modify Eq. (1) to include an upper bound on pollution per unit of output and denote production units' quasi-rents as π^{θ}. Using the definition of production units' quasi-rents, we transition from the micro to the macro level. Technically, a unit remains active if $\beta \in [0, \theta_{A,1}]$ and $\pi^{\theta} \geq 0$, and a unit adopts clean technology in the first period if $\beta \in (\theta_{A,1}, \theta_{A,1}/(1-\gamma)]$ and expected quasi-rents are not negative. Otherwise, a unit becomes idle. Similarly, we can describe second-period survival and modification regions.

Monetary charges that equal the marginal social damage result in Pareto optimality. However, estimating the social damage function is challenging (Baumol and Oates, 1971). An alternative cost-efficient approach introduced in the literature, assumes policy is set to achieve a predetermined aggregate pollution level. Building on this alternative approach, we assumed that at the beginning of the game Party A chooses the per-period expected aggregate level of pollution $\overline{\mathbb{Z}}$ (e.g., stock of pollution should not result in global average temperatures increasing by more than 2^0C of their pre-industrial level), and then period 1 begins and Party A sets policy. Furthermore, assume the intensity upper bound is set at the beginning of each period: $\theta_{A,1}$ for the first period and $\theta_{A,2}$ for the second. Note that although pollution is constrained by a predetermined aggregate level in period 1 (i.e., $\mathbb{Z}_{A,1} \leq \overline{\mathbb{Z}}$), political uncertainty results in policy containing only the expected value of the pollution stock in period 2 (i.e., $\alpha\mathbb{Z}_{A,2} + (1-\alpha)\mathbb{Z}_{B,2} \leq \overline{\mathbb{Z}}$). Formally, the Lagrangian of Party A's period 1 constraint-maximization problem is

$$\mathcal{L}_1 = W_{A,1} + \delta\big(\alpha W_{A,2} + (1-\alpha)W_{B,2}\big) + \lambda_1\big(\mathbb{Z}_{A,1} - \overline{\mathbb{Z}}\big)$$
$$+ \lambda_2\big(\alpha\mathbb{Z}_{A,2} + (1-\alpha)\mathbb{Z}_{B,2} - \overline{\mathbb{Z}}\big)$$

where $0 < \lambda_1, \lambda_2$ are the Kuhn-Tucker multipliers. Party A sets $\theta_{A,1}$ and, if elected in period 2, sets $\theta_{A,2}$. In period 2, it chooses an intensity upper bound $\theta_{A,2}$ that maximizes Eq. (6) subject to $\mathbb{Z}_{A,2} \leq \overline{\mathbb{Z}}$. The Lagrangian of Party A's period 2 constraint-maximization problem is

$$\mathcal{L}_2 = W_{A,2} + \mu\big(\mathbb{Z}_{A,2} - \overline{\mathbb{Z}}\big)$$

where $0 < \mu$ is the Kuhn-Tucker multiplier. However, if Party B is elected in the second period, then $\theta_{B,2} = \bar{\beta}$ (recall that Party B does not care about the environment).

Assumption 1: Output capacity distribution function $g(\beta, x)$ *is a single-peak distribution function with the peak up and to the right of the equilibrium outcome.*

Assumption 2: $\frac{\partial^2}{\partial Q^2}(CS + PS) \leq 0 \leq \frac{\partial}{\partial Q}(CS + PS)$.

While Assumption 1 suggests that most production units are polluting units, Assumption 2 states that in the neighborhood of the equilibrium solution the economic surplus (i.e., producer plus consumer surpluses) increases with quantity at a decreasing rate. Proposition 2 is as follows:

Proposition 2. *Assume expected aggregate pollution is set at a predetermined per-period aggregate level* $\bar{\bar{\mathbb{Z}}}$. *Then, the equilibrium intensity upper bound equates the marginal economic cost of regulation (i.e., the effect of the standard on consumer and producer surpluses) to the marginal pollution damage, and this equilibrium is unique.*

Given Assumptions 1 and 2, the F.O.C. of the constraint-maximization problems (i.e., ${\partial \mathcal{L}_1}/{\partial \theta_{A,1}} = 0$ and ${\partial \mathcal{L}_2}/{\partial \theta_{A,2}} = 0$) suggest that marginal economic cost of regulation *decreases* in θ while the marginal pollution damage *increases* – a less stringent standard, and therefore a larger θ, results in a smaller impact on the consumer and producer surpluses yet leads to more pollution and thus larger marginal pollution damage. The F.O.C. of the first period constraint-maximization problem (i.e., ${\partial \mathcal{L}_1}/{\partial \theta_{A,1}} = 0$) also suggests that the optimal intensity upper bound increases with the decay parameter and that the intensity upper bound is largest if pollution is a flow.

Next, we compare the regulatory outcome of a tax to that of an intensity upper bound and discuss employment, output, and adoption.

VI. Comparing a Tax to a Standard: The Pareto Distribution

This section compares a tax to an intensity upper bound, assuming a generalized Pareto output-capacity distribution function. This distribution function has been used extensively in the trade literature (Helpman et al., 2007; Melitz & Ottaviano, 2008; Chaney, 2008), and its aggregation across firms yields a Cobb-Douglas production function (Houthakker, 1955-1956). Employing a specific distribution function allows us to numerically, as well as conceptually, quantify and evaluate the differences between a tax and an intensity upper bound and assess their impact on the power utility sector in the U.S.

Technically, assume production units distributed according to the following generalized Pareto distribution function:

$$g(\beta, x) = \mathrm{A}\beta^{\varphi_1 - 1} x^{\varphi_2 - 1} \; for \; \mathrm{A}, \varphi_1, \varphi_2 > 0.$$

This functional form suggests that when $\varphi_1 = 1$ and $\varphi_2 = 1$, the density function is a uniform distribution function where $g(\beta, x) = \mathrm{A}$ for $\left\{\{\beta, x\} \mid 0 \leq \beta \leq \bar{\beta}, 0 \leq x \leq \bar{x}\right\}$ and 0 otherwise. However, when $\varphi_1 < 1$ ($\varphi_2 < 1$), the density function places more weight on the low-polluting (efficient) production units. However, if $\varphi_1 > 1$ ($\varphi_2 > 1$), then the density function places more weight on the high-polluting (inefficient) units.

We use the generalized Pareto distribution function to derive the survival regions and calculate output, employment, and adoption. We calculate the value of these variables for both the tax and the standard regimes and use these calculations to compare the two aforementioned policy instruments.

The parameters used for the calculations are depicted in Table 1, where total employment in the power utility sector is used to calibrate the productivity parameter (i.e., A) using Eq. (2) and the definition of X^0. The Energy Information Administration (EIA) included data on 6,668 plants that generated a total of about 4 billion megawatts.[3] We also use information on the power plant industry in the U.S. to derive estimates of price and investment. We assume a competitive industry that does not affect the equilibrium price. We also assume more density given to high-polluting and inefficient units, a 50% decline in upfront costs in the second period, and that the probability that Party A is reelected is 55%.

Parameter	Value	Parameter	Value	Parameter	Value
$\mathbf{A}$	2115.3	φ_1	2.0	φ_2	2.0
$\mathbf{p_{A,1}}$	10.34	$\mathbf{p_{A,2}}$	10.34	$\mathbf{p_{B,2}}$	10.34
$\mathbf{I_1^m}$	1.5982	$\mathbf{I_2^m}$	0.79909	ω	$1/2$
$\boldsymbol{\delta}$	0.95	$\boldsymbol{\alpha}$	0.55	$\boldsymbol{\gamma}$	0. 5
$\boldsymbol{\rho}$	0.05	$\boldsymbol{\xi}$	$9.8 * 10^{-5}$	$\bar{\boldsymbol{\beta}}$	1
$\boldsymbol{\Psi}$	0.75				

Table 1. *The baseline parameters.*

Our assumptions suggest that in the unregulated environment, the economic conditions yield 56,540 active production units (using Eq. (2) and the definition of Y^0), each generating 70,750 megawatts (recall that although production technology varies across the different units, each production unit is

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[3] Data are available at http://www.eia.gov/electricity/data/browser/

assumed to generate one unit of output, which in the calibration is equivalent to 70,750 megawatts), with pollution flow of 37,390 units (using Eq. (2) and the definition of Z^0). Assuming the power utility sector is producing 30% of annual greenhouse gases produced in the U.S., and given that the U.S. generated about 6,500 million tons of CO_2 in 2012,[4] the result is 0.05 million tons of CO_2 per pollution unit ($= 6500 \cdot 0.3/37390$).

In what follows, assume predetermined pollution stock in period 1 of 20,158 units (a reduction of 46.5% in the pollution level). This level of pollution is compatible with an intensity standard of $\theta_{\mathrm{A},1} = 0.43759$ and $\theta_{\mathrm{A},2} = 0.39591$ and with an optimal (dynamic) tax of $\tau_{\mathrm{A},1} = 6.58$ and $\tau_{\mathrm{A},2} = 3.95$ per pollution unit. Because of political uncertainty and pollution not being a flow, the dynamic Pigovian tax of period 1 is smaller than the optimal dynamic tax; that is, the dynamic Pigovian tax is $4.89 < 6.58 = \tau_{\mathrm{A},1}$.

However, the question of how adoption rates vary across regimes remains. We address this question by deriving the output, employment, and adoption rates under the two alternative regimes.

A. The Tax Regime

Building on the aforementioned assumptions, we describe the survival region $\mathrm{R}^{\mathrm{A},1}$ in the β-x plane assuming a tax regime. Formally, let first-period expected quasi-rents $\tilde{\pi}_i^{\tau}$ for $i \in \{0,1,2\}$ denote production units that made a technology choice (0 denotes units that do not adopt, whereas *i=1* or *i=2* denotes units that adopt technology in period *i*) and assume units are indifferent about remaining active; that is, $\tilde{\pi}_i^{\tau} = 0$. The slopes of these lines are

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[4] Data are available at http://www.epa.gov/climatechange/Downloads/ghgemissions/US-GHG-Inventory-2014-Chapter-2-Trends.pdf

$$-\frac{\partial\widetilde{\pi}_1^\tau/\partial\beta}{\partial\widetilde{\pi}_1^\tau/\partial \mathrm{x}} = -2.1106 > -\frac{\partial\widetilde{\pi}_2^\tau/\partial\beta}{\partial\widetilde{\pi}_2^\tau/\partial \mathrm{x}} = -3.9029 > -\frac{\partial\widetilde{\pi}_0^\tau/\partial\beta}{\partial\widetilde{\pi}_0^\tau/\partial \mathrm{x}} = -4.4322$$

and their intercepts are $\mathrm{x}(\beta = 0, \widetilde{\pi}_0^\tau = 0) = 10.3400 > x(\beta = 0, \widetilde{\pi}_2^\tau = 0) = 10.1259 > x(\beta = 0, \widetilde{\pi}_1^\tau = 0) = 9.0671$. We depict $\widetilde{\pi}_i^\tau$ for $i \in \{0,1,2\}$ in Figure 1, and note that DCBEO is the survival region $\mathrm{R}^{\mathrm{A},1}$. The tax policy results in inefficient and dirty units exiting the industry (i.e., units located in region $\mathrm{R}^0 - \mathrm{R}^{\mathrm{A},1}$). The effect of the tax regime on output, employment, and adoption is shown in Table 2. Given that a production unit generates 70,750 megawatts, a tax regime yielded a reduction of 1.72 billion megawatts in electricity generated ($= \frac{(56{,}540-32{,}241)\cdot 70{,}750}{10^9}$).

	No Regulation	**Tax Regime**	**Standard Regime**	**% Increase Relative to the Tax**
Output	56,540	32,241	35,801	10.46%
Employment	389,750	171,480	225,590	31.55%
Pollution	37,693	20,158	20,158	0%
Adoption (output)		21,290	24,974	17.33%

Table 2. *The effect of the period 1 policy instruments.*

Some of the active production units adopt the clean technology in the first period, but others do not. We characterize these early adopters and separate them from the late adopters and identify units that do not adopt the technology in either period 1 or period 2 (see Appendix B):

a. The line $\pi_1^\tau = \pi_0^\tau$ *(i.e., line HA in Figure 1):*

$$x_{0,1} = 44.3222 \cdot \beta - 16.3915 \tag{10}$$

b. The line $\pi_1^\tau = \pi_2^\tau$ *(i.e., line LC in Figure 1):*

$$x_{1,2} = 33.7355 \cdot \beta - 12.1092 \tag{11}$$

c. The line $\pi_2^\tau = \pi_0^\tau$ *(i.e., line MB in Figure 1):*

$$\beta = 0.4045 \tag{12}$$

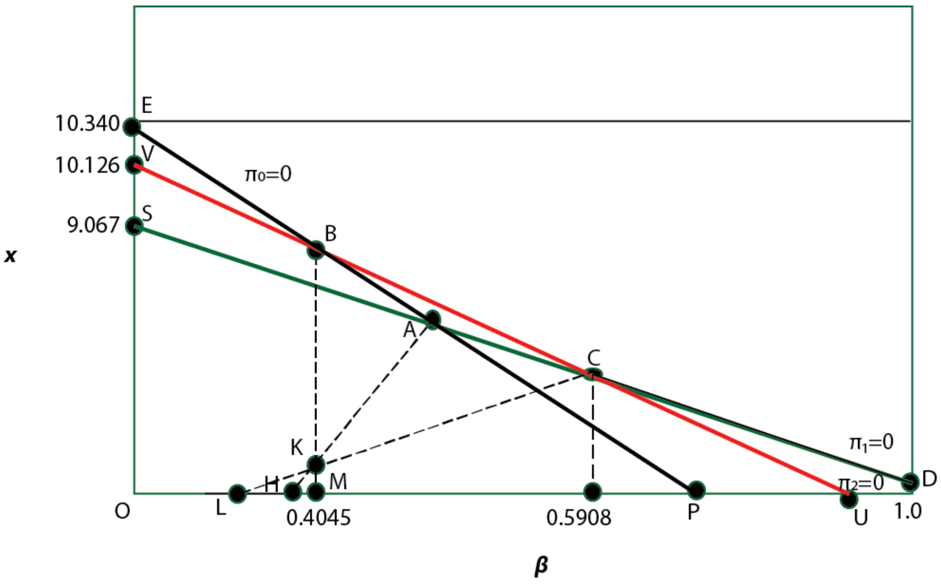

Figure 1. First-period survival region under a tax.

We use the above-defined lines, together with the boundary of the survival region, to identify units that adopt the new technology in period 1. Units located in region HKCD, namely, R_1^m, adopt the clean technology in the first period.

These are the efficient yet polluting units.

However, if Party A is reelected, then some of the units that did not adopt the clean technology in the first period may adopt it in the second period. The late adopters are less efficient but less polluting units than the early adopters. The late adopters purchase the clean technology only if Party A is reelected, and they make the purchase at a lower upfront cost than the early adopters (recall that $\rho = 0$ in period 2, but that $\rho > 0$ in period 1 and that $I_2^m = (1-\omega)I_1^m$ for $\omega = 0.5 > 0$). In the numerical model, 21,290 production units (i.e., power plants) adopt the clean technology in period 1, while 171,480 production units are active. In the second period, because investment is irreversible, the number of active units does not change. However, the number of active units that adopt the cleaner technology increases by 10,580 units. Note that although more output is produced via a tax in period 2 (see Table 3), more people are employed under a standard (7.7% more people are employed under a standard).

	Tax Regime	**Standard Regime**	**% Change**
Output	32,410	29,759	-8.8%
Employment	171,480	184,660	7.7%
Adoption (output)	10,580	20,897	97.5%

Table 3. *The effect of the policy instrument in period 2.*

B. Adoption and the emission upper bound

In section 5, we modify Eq. (1) to include an upper bound on pollution per unit of output and identify early adopters (i.e., characterize production units that adopted the clean technology in period 1). We then transition from the micro to the macro level. We depict this first-period survival region in Figure 2.

Our baseline model suggests that under an intensity upper bound 24,970 production units adopt the clean technology in the first period, whereas the total number of active units in period 1 is 35,801 (Table 2). Let $R_M^{\theta_{A,1}}$ denote the first-period adoption region (i.e., the green rectangle in Figure 2), and let $\mathrm{R}_\mathrm{A}^{\theta_{\mathrm{A},1}}$ denote the region where active units do not adopt the clean technology in period 1. The union of these two regions is the survival region, namely, $\mathrm{R}^{\theta_{\mathrm{A},1}} = \mathrm{R}_\mathrm{M}^{\theta_{\mathrm{A},1}} \cup \mathrm{R}_\mathrm{A}^{\theta_{\mathrm{A},1}}$ (i.e., the survival region 35,801 = 10,831 + 24,970).

While an upper bound does not affect operation costs, it does affect upfront costs, leading units with large pollution output coefficients to modify their technology (i.e., $\{\beta, x\} \in R_M^{\theta_{A,1}}$) or exit the industry and become idle (i.e., $\{\beta, x\} \in R^0 - R^{\theta_{A,1}}$). Our analysis suggests that a standard leads to about 10% more production units remaining active, thus resulting in a significantly lower impact on the amount of megawatt generated that becomes idle because of regulation (see Figure 2). It also results in almost 36% more employment in the sector and about 17% more units adopting the clean technology than under a tax.

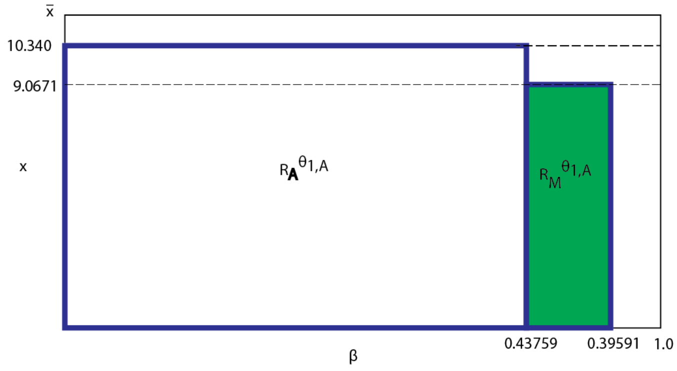

Figure 2. First-period survival region under a standard.

The Clean Air Act of 1970 gave the EPA authority to regulate motor vehicle pollution and introduce emission control policies. The advent of first-generation catalytic converters in 1975 significantly reduced hydrocarbon and carbon monoxide emissions (see EPA website – http://www.epa.gov); it pushed dirty technologies out of the market and resulted in fewer emissions from motor vehicles.

Similar to the tax scenario, in this scenario, the second-period outcome is also conditional on the party in power. The second-period survival region, assuming Party B is in power, equals that of the first period ($R^{\theta_{B,2}} = R^{\theta_{A,1}}$ and a total of $35{,}801$ active units). Active units in period 1 (i.e., units in region $R^{\theta_{A,1}}$) remain active in period 2. Furthermore, units that modified their technology in the first period, namely, $R_M^{\theta_{A,1}}$ (i.e., $24{,}974$ active units that modified their technology), continue using the cleaner technology in the second period. However, if Party A remains in power, then the survival region may shrink further and we may observe late adopters. Then, the possible outcomes are as follows:

a. The first-period upper bound is stricter than that of the second period; that is, $\theta_{A,1} \leq \theta_{A,2}$. This outcome yields a second-period survival region that equals that of the first period, that is, $R^{\theta_{A,2}} = R^{\theta_{A,1}}$.

b. The second-period upper bound is stricter than that of the first period (which is the outcome of the numerical example); that is, $\theta_{A,1} > \theta_{A,2}$. This outcome results in late adopters denoted $R_M^{\theta_{A,2}}$. In this scenario, early adopters may serve as a bridge to a less polluting industry, where the transition to a cleaner production structure is gradual.

b.i. Policy affected the extensive margins and led units to exit the industry in period 2. The units that exited the industry in period 2 belong to the early adopters group, namely, $R_M^{\theta_{A,1}}$. The numerical simulation suggests that when the predetermined pollution results in an intensity upper bound $\theta_{A,1} = 0.4376$ and $\theta_{A,2} = 0.3959$, 6,042 units that adopted the clean technology in period 1 exit the industry in period 2. Many view natural gas-fired power plants as a short-term substitute to aging coal-fired power plants that will be phased out in the long run when technologies with significantly lower carbon footprints become economically viable.

b.ii. Policy also influenced the intensive margins, resulting in active units adopting the alternative technology in period 2. In the numerical example, an addition of 1,965 production units adopted cleaner technology only in the second period.

Returning to our real-world example, EPA emission control policies became progressively more stringent after their introduction in the early 1970s. From 1975 to 2014, light vehicles' average CO_2 grams per mile declined by about 50% while miles per gallon increased by more than 100%.[5]

Our dynamic framework suggests that conditions exist where a standard yields more adoption than a tax, as well as more employment and lower prices. While the economically efficient instrument (i.e., the tax) results in a large impact on the extensive margins leading many units to exit and become idle, the standard seems like the politically efficient instrument of choice because it emphasizes the effect on the intensive margins much more. The standard results in significantly

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[5] See http://www.epa.gov/otaq/fetrends.htm

fewer units exiting and more employment, but much more adoption in the short term. The increase in adoption yields policy outcomes that are more resilient to political change.

A broad set of parameters results in a standard yielding more output, employment, and adoption in the short run than a tax. For instance, we obtain similar outcomes while revising our baseline parameters (i.e., assuming $\varphi_1 = 3.5 = \varphi_2$ and/or varying the value of γ between 0.15 and 0.85, as well as calibrating the model to a different set of decay parameters).

VII. Discussion and Concluding Remarks

This paper reevaluates the proposition that market-based instruments should be used to address long-term environmental problems. The paper shows that in a world with uncertainty regarding future governments, establishing a pollution tax in industries relying on capital-intensive technologies may result in the optimal dynamic tax being larger than the Pigovian tax. The paper also shows that, given predetermined aggregate pollution, a standard may result in higher adoption rates than a tax, as well as more employment, higher output, and lower prices.

The foundational work of Weitzman (1974) introduced demand and supply uncertainties and concluded that under certain conditions quantity instruments are preferred over price instruments as a mode of regulation. This work expands that line of thinking and shows that a standard may be the preferred mode of regulation because of political uncertainty. Political uncertainty regarding future elections may induce governments to employ a standard to regulate the environment. The standard is less costly politically (i.e., more employment), and it achieves a pre-determined level of aggregate pollution with more adoption and thus solidifies the transition toward clean technologies more than a tax. It is interesting that although economists argue for the use of price instruments, politicians are much keener to employ an intensity upper bound, as the examples in the introduction suggest.

Although the model analyzed above suffices to shed new light on the political economy of environmental policy while highlighting the benefits of using an intensity upper bound, this work can be extended in various ways. For instance, we can assume non-random elections. This is motivated by the real world where elections are not random but the outcome of actions taken by the incumbent government. However, how does the analysis change when elections are influenced by existing policy? Assume, for simplicity, that the consumer does not factor into her/his calculation the benefits of policy to the environment (e.g., the horizon is too long and/or the benefits to a consumer are too small to notice). Then, environmental policy is costly to the incumbent government and will dampen the stringency of the policy chosen in the first period but result in a more stringent policy in the second period if Party A is reelected.

A second extension introduces commitment. However, our analysis suggests that commitment is not credible. When Party A establishes a binding policy in period 1, the policy choice will be the average across the two periods. Assuming the discretionary tax is higher in the first period suggests that a binding policy will dampen the first-period tax but increase the second-period tax. However, such commitment is not optimal: Party A’s choice is less preferred than a policy choice without commitment, and Party B clearly does not benefit from a policy that is grandfathered to it.

Capital-intensive industries (e.g., power plants) are the main source of anthropogenic emissions. These industries make large capital investments and are not quick to make changes. This study suggests that environmentally conscious governments can exploit this production structure to tie the hands of future governments and yield a permanent environmental change. It also provides political-economic justification for forcing technological change. In future work, we plan to explore empirically the dynamics of capital-intensive industry (i.e., the power sector) and how it responds to regulation. This work will shed new light, for example, on the implications of the Obama administration regulations regarding carbon pollution of existing power plants under Section 111(d) of the Federal Clean Air Act.

More generally, while building on the presumption that political survival of parties and individuals is uncertain, this work contributes to the strand of literature that aims to understand politicians' incentives to manipulate current policy and influence both future elections and policy choices of future governments. An example of current policy aiming to influence choices of future governments is the Vienna nuclear deal signed by Iran and the P5+1 (the permanent members of the UN Security Council and Germany) that aspires to prevent the manufacturing of nuclear technologies by Iran. Our study shows that choice of policy instrument may result in more adoption, thus making the reversal of policy outcomes in future periods less attractive.

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Appendices:

Appendix A: Proof of Proposition 1

Before depicting the proof of Proposition 1, we introduce the following notation. Let ${\pi_j}^{\tau,t}$ denote production unit quasi-rents in period t, and let subscript *j* denote early adopters (i.e., *j=1*), late adopters (i.e., *j=2*), or units that do not adopt (i.e., *j=0*).

We use this notation to define the first- and second-period survival regions:

I) The *first-period survival region* is

$$R_{A,1} = \left\{\{\beta, x\}\middle|0 \leq \beta \leq \bar{\bar{\beta}}, 0 \leq x \leq \bar{\bar{X}}(\beta)\right\}$$

where $\bar{\bar{X}}(\beta) \equiv max\{\overline{\overline{x_0}}(\beta), \overline{\overline{x_1}}(\beta), \overline{\overline{x_2}}(\beta)\}$, and the following curves define $\bar{\bar{\beta}}$, $\overline{\overline{x_0}}(\beta), \overline{\overline{x_1}}(\beta),$ and $\overline{\overline{x_2}}(\beta)$:

1) $\pi_1^{\tau,1}(\beta, x = 0) = 0 \Rightarrow \bar{\bar{\beta}}$ (i.e., point D in Figure 1): $\bar{\bar{\beta}} = \frac{P - I_1^m}{T \cdot (1-\gamma)}$

2) $\pi_0^{\tau,1}(\beta, x) = 0 \Rightarrow \overline{\overline{x_0}}(\beta)$ (i.e., line EP in Figure 1): $\overline{\overline{x_0}}(\beta) = \frac{P - T \cdot \beta}{(1+\delta)}$

3) $\pi_1^{\tau,1}(\beta, x) = 0 \Rightarrow \overline{\overline{x_1}}(\beta)$ (i.e., line SD in Figure 1): $\overline{\overline{x_1}}(\beta) = \frac{P - T \cdot (1-\gamma) \cdot \beta - I_1^m}{(1+\rho)(1+\delta)}$

4) $\pi_2^{\tau,1}(\beta, x) = 0 \Rightarrow \overline{\overline{x_2}}(\beta)$ (i.e., line VU in Figure 1): $\overline{\overline{x_2}}(\beta) = \frac{P - T \cdot \beta - \delta \cdot \alpha \cdot (I_2^m - \tau_{A,2} \cdot \gamma \cdot \beta)}{(1+\delta)}$.

Note that the set $\left\{\{\beta, x\} \mid \beta \in \left[0, \bar{\bar{\beta}}\right], x = max\{\overline{\overline{x_0}}(\beta), \overline{\overline{x_1}}(\beta), \overline{\overline{x_2}}(\beta)\}\right\}$ defines the line EBCD in Figure 1.

II) The *second-period survival region* is

$$R_{A,2} = \left\{\{\beta, x\}\middle|0 \leq \beta \leq min\left\{\bar{\bar{\beta}}, \breve{\beta}\right\}, 0 \leq x \leq min\left\{\bar{\bar{X}}, \breve{X}\right\}\right\}$$

where $\breve{X} \equiv max\{\breve{x_0}(\beta), \breve{x_1}(\beta), \breve{x_2}(\beta)\}$, and the values $\breve{\beta}, \breve{x_0}(\beta), \breve{x_1}(\beta), \breve{x_2}(\beta)$ are defined as follows:

1) $\pi_1^{\tau,2}(\beta, x = 0) = 0 \Rightarrow \breve{\beta} = \frac{p_{A,2}}{\tau_{A,2} \cdot (1-\gamma)}$

2) $\pi_0^{\tau,2}(\beta, x) = 0 \Rightarrow \breve{x_0} = p_{A,2} - \tau_{A,2} \cdot \beta$

3) $\pi_1^{\tau,2}(\beta, x) = 0 \Rightarrow \breve{x_1} = \frac{p_{A,2} - \tau_{A,2} \cdot (1-\gamma) \cdot \beta}{(1+\rho)}$

4) $\pi_2^{\tau,2}(\beta, x) = 0 \Rightarrow \breve{x_2} = p_{A,2} - \tau_{A,2} \cdot (1-\gamma) \cdot \beta - I_2^m$

These definitions suggest that $R_{A,1}(\tau_{A,1}, \tau_{A,2})$ and $R_{A,2}(\tau_{A,1}, \tau_{A,2})$. Because policy $\tau_{A,1}$ affects both first-period and second-period survival regions, it affects not only $CS_{A,1}$ $PS_{A,1}$, and $\mathbb{Z}_{A,1}$, but also $CS_{j,2}$ $PS_{j,2}$, and $\mathbb{Z}_{j,2}$ for j=A,B.

We use the aforementioned survival regions to characterize the optimal solution to Party A, while beginning with period 2.

Party A chooses $\tau_{A,2}$ to maximize Eq. (6) and sets $\tau_{A,2} = 2\xi\mathbb{Z}_{A,2}$ (i.e., the static second-period Pigovian tax).

Party A chooses $\tau_{A,1}$ to maximize Eq. (5) and the First Order Coditions (F.O.C.) of this maximization problem is

$$\begin{aligned} 0 &= \frac{\partial W_{A,1}}{\partial \tau_{A,1}} + \delta\left[\alpha \frac{\partial W_{A,2}}{\partial \tau_{A,1}} + (1-\alpha)\frac{\partial W_{B,2}}{\partial \tau_{A,1}}\right] \\ &= \left(\frac{\partial CS_{A,1}}{\partial \tau_{A,1}} + \frac{\partial PS_{A,1}}{\partial \tau_{A,1}}\right) + \delta(1-\alpha)\left(\frac{\partial CS_{B,2}}{\partial \tau_{A,1}} + \frac{\partial PS_{B,2}}{\partial \tau_{A,1}}\right) \\ &\quad - \left[\left(2\xi\mathbb{Z}_{A,1} \quad \delta(1 \quad \Psi)\left(\alpha 2\xi\mathbb{Z}_{A,2} \quad (1 \quad \alpha)2\xi\mathbb{Z}_{B,2}\right)\right)\frac{\partial Z_{A,1}}{\partial \tau_{A,1}}\right. \\ &\quad \left. + \delta(1 \quad \alpha)2\xi\mathbb{Z}_{B,2}\frac{\partial Z_{B,2}}{\partial \tau_{A,1}}\right] \end{aligned}$$

In deriving the F.O.C., we use the chain rule and employ the envelope theorem and thus

$$\frac{\partial W_{A,2}}{\partial \tau_{A,1}} = \underbrace{\left(\frac{\partial CS_{A,2}}{\partial R_{A,2}} + \frac{\partial PS_{A,2}}{\partial R_{A,2}} - \frac{\partial C_{A,2}}{\partial R_{A,2}}\right)}_{=0} \frac{\partial R_{A,2}}{\partial \tau_{A,1}} - \frac{\partial C_{A,2}}{\partial R_{A,1}} \frac{\partial R_{A,1}}{\partial \tau_{A,1}} = -2\xi \mathbb{Z}_{A,2}(1 \quad \Psi) \frac{\partial Z_{A,1}}{\partial \tau_{A,1}}$$

(follows from the F.O.C. of the second period assuming Party A remains in power). Furthermore, because investment is irreversible and $\tau_{B,2} = 0$, the optimal first-period tax per pollution unit is

$$\tau_{A,1} = 2\xi \mathbb{Z}_{A,1} \qquad \underbrace{\delta(1 \quad \Psi)2\xi\left(\alpha \mathbb{Z}_{A,2} \qquad (1 \quad \alpha)\mathbb{Z}_{B,2}\right)}_{The\ stock\ effect}$$
$$+ \qquad \underbrace{\delta(1 \quad \alpha)2\xi \mathbb{Z}_{B,2}}_{The\ political\ uncertainty\ effect}$$

The final step of the proof is to show that the optimal tariff scheme derived above yields, in equilibrium, the solution that maximizes Party A's objective function. To derive this conclusion, recall that a production unit is active and produces at capacity if its profit is non-negative but becomes idle otherwise, and that $g(\beta, x)$ is a smooth function with compact support. Furthermore, assuming that policy is binding suggests that the marginal unit earns zero profits; that is, the marginal unit equates its benefit from producing one unit with the cost of the pollution it creates. Let $\tilde{\tau}_{A,t}$ for $t \in \{1,2\}$ denote the policy in equilibrium in period *t* and assume $\tilde{\tau}_{A,1} = \tau_{A,1}$ and $\tilde{\tau}_{A,2} = \tau_{A,2}$. By construction, marginal production units under the optimal tariff scheme are the marginal units in the equilibium and vis versa. Because production units' expected profits decline with β and x, the tax rates, $\tilde{\tau}_{A,1}$ and $\tilde{\tau}_{A,2}$, maximize $V_{A,1}$.

The proposition follows.

Q.E.D.

Appendix B:

Using Eqs. (7) and (9), we derived the linear relationship between input-output and the pollution-output coefficients of production units that are indifferent between adopting the modification in period 1 or not adopting it at all (i.e., the line at which $\pi_1^{\tau} = \pi_0^{\tau}$):

$$x_1(\beta) = \frac{\gamma \cdot \tau_{A,1} + \delta \cdot \alpha \cdot \gamma \cdot \tau_{A,2}}{\rho \cdot (1+\delta)} \cdot \beta - \frac{I_1^m}{\rho \cdot (1+\delta)}. \tag{1d}$$

Using Eqs. (7) and (8), we derived the line at which $\pi_1^\tau = \pi_2^\tau$:

$$x_2(\beta) = \frac{\gamma \cdot \tau_{A,1}}{\rho \cdot (1+\delta)} \cdot \beta - \frac{I_1^m - \delta \cdot \alpha I_2^m}{\rho \cdot (1+\delta)}. \tag{2d}$$

Finally, using Eqs. (8) and (9), we derived the line at which $\pi_2^\tau = \pi_0^\tau$:

$$\beta = \frac{I_2^m}{\tau_{A,2} \cdot \gamma} \tag{3d}$$

Q.E.D.