



AgEcon SEARCH
RESEARCH IN AGRICULTURAL & APPLIED ECONOMICS

The World's Largest Open Access Agricultural & Applied Economics Digital Library

This document is discoverable and free to researchers across the globe due to the work of AgEcon Search.

Help ensure our sustainability.

Give to AgEcon Search

AgEcon Search
<http://ageconsearch.umn.edu>
aesearch@umn.edu

*Papers downloaded from **AgEcon Search** may be used for non-commercial purposes and personal study only. No other use, including posting to another Internet site, is permitted without permission from the copyright owner (not AgEcon Search), or as allowed under the provisions of Fair Use, U.S. Copyright Act, Title 17 U.S.C.*

The Political Economy of Embodied Technologies

Gal Hochman

Rutgers University,

gal.hochman@rutgers.edu

David Zilberman

University of California Berkeley

zilber11@berkeley.edu

**Selected Paper prepared for presentation at the 2016 Agricultural & Applied Economics
Association Annual Meeting, Boston, Massachusetts, July 31-August 2**

Copyright 2016 by Gal Hochman and David Zilberman. All rights reserved. Readers may make verbatim copies of this document for non-commercial purposes by any means, provided that this copyright notice appears on all such copies.

The Political Economy of Embodied Technologies

BY Gal Hochman^{*} and David Zilberman^{† ‡}

MAY 2016

^{*} Corresponding author – Hochman: Rutgers University, 55 Dudley Rd., New Brunswick, NJ 08816 (email: gal.hochman@rutgers.edu)

[†] Zilberman: University of California Berkeley, zilber11@berkeley.edu

[‡] The authors thank Kathleen Segerson for the conversations they had and comments she made on earlier drafts, which significantly improved this work and its presentation. Any remaining errors are the authors' doing.

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

Keywords: Embodied technologies, political uncertainty, standard, tax, environmental policy

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

27 chlorofluorocarbons (Ashford et al., 1985; McFarland, 1992), the development of
28 flue gas desulfurization systems for SO₂ control in the power sector (Popp, 2003;
29 Taylor et al., 2005), and the control of automobile emissions (Jaegul et al., 2010),
30 among many other examples. While much of the literature takes a welfare
31 economic perspective, we approach the problem from a political economic
32 vantage point.

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

48 This paper presents a political economic framework of a model for the
49 selection of policy tools in the context of a choice of environmental policy. This
50 framework will provide a new perspective to the literature that aims to explain the
51 use of financial incentives versus direct control policies to address externality
52 problems. The model developed is a two-period model that aims to capture a
53 dynamic feature of political decision making, namely, the transition among ruling

54 parties. The model is based on the presumptions that (i) policy makers at the
55 present aim to design policy outcomes that will survive a political transition and
56 (ii) production units employ a capital-intensive technology that consists of several
57 activities, each with its own fixed proportion properties (i.e., a putty-clay
58 technology). The empirical literature has shown that these technologies – the
59 putty-clay technologies whereby the production coefficients are fixed in the short
60 run – fit well the energy sector (Dasgupta, 1970; Fuss, 1978).

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

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

79 However, although environmental policy influences future outcomes by

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

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

107 2005, which was revised in 2007, and led to the development of a flourishing
108 corn-ethanol industry.

109 The paper proceeds as follows. The conceptual model is introduced in
110 section 2. Section 3 describes the two-period game. The analysis begins in section
111 4, where the tax equilibrium is derived. We switch to a pollution-intensity upper
112 bound in section 5 and compare the outcome of a tax to the outcome of an
113 intensity upper bound in section 6, where we also calculate the effect of policy on
114 adoption. General policy discussion and concluding remarks are presented in
115 section 7.

116 **II. The Conceptual Model**

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

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

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

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

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

$$\pi^0 \equiv p - x, \quad (1)$$

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

154 The production unit may also make irreversible investments, thus

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

161 Technically, assume that investment decisions are discrete choices and
162 that a production unit may invest $I_t^m > 0$ and modify its existing technology via
163 adopting the cleaner technology. Let superscript m denote the modified
164 technology, let subscript $t = \{1,2\}$ denote period t , and assume the modified
165 technology reduces emissions by $\gamma \geq 0$. The production unit may invest $I_1^m > 0$
166 in period 1 and modify its pollution-intensity coefficient, that is, $\beta^m = (1 - \gamma) \cdot$
167 β . However, the new technology may also affect the input-output coefficient. Let
168 $\rho \geq 0$ denote the effect of the adopted technology on production costs and
169 assume $x^m = (1 + \rho) \cdot x$. These assumptions capture the idea that while the
170 average annual fuel cost of generating one-megawatt hour using fossil steam is
171 \$3.73 U.S., it is \$6.71 U.S. using hydroelectricity – that is, it is cheaper to
172 produce one-megawatt hour using the polluting technologies than the cleaner
173 ones.¹

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

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

180 upfront capital and does not affect production costs. Formally, we assume $I_2^m =$
 181 $(1 - \omega)I_1^m$ where $\omega > 0$ and adopting clean technology in the second period
 182 does not change the per-unit production costs, that is, $\rho = 0$. For simplicity, we
 183 also assume that $\gamma_2 = \gamma_1 (\equiv \gamma)$.

184 To derive the aggregate supply of output, denoted by Y , we follow
 185 Hochman and Zilberman (1978) – who followed Johansen (1972) – and define an
 186 output capacity distribution function $g(\beta, x)$. The output capacity of production
 187 units located in the set $(\beta, \beta + d\beta) \times (x, x + dx)$ for small $d\beta$ and dx are
 188 simply $g(\beta, x)d\beta dx$. We assume that $g(\beta, x)$ is a smooth function with
 189 compact support. This output-capacity distribution function is used to define the
 190 output produced by units located in region $R \subseteq (0, \bar{\beta}) \times (0, \bar{x})$, that is, $Y^0 \equiv$
 191 $\int \int_R g(\beta, x) d\beta dx$.

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

$$195 \quad R^0 \equiv R(p) = \{(\beta, x) \mid 0 \leq \beta \leq \bar{\beta}, 0 \leq x \leq p\},$$

196 assuming $p < \bar{x}$. Put differently, production units $R - R^0 \equiv \{(\beta, x) \mid 0 \leq \beta \leq$
 197 $\bar{\beta}, p < x \leq \bar{x}\}$ remain idle.

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

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

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

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

200 Assume a downward-sloping demand function $Q = D(p)$, $\partial D(p)/$
 201 $\partial p < 0$. Then, the equilibrium price is determined by $Y^0 = Q$. At this
 202 equilibrium price (p^0), the marginal firm earns zero quasi-rents (i.e., $x =$
 203 p^0). Then, assuming pollution does not affect consumers' benefit from the
 204 good consumed, consumer surplus (CS) and producer surplus (PS) are,
 205 respectively,

$$CS^0 = \int_{p^0}^{\infty} D(p) dp \tag{3}$$

$$PS^0 = p^0 \cdot Y^0 - X^0$$

206 The industry generates a flow of pollution, and this flow generates a stock
 207 of pollution. Let $\mathbb{Z}_t = Z_{t-1}(1 - \Psi) + Z_t$ denote the pollution stock in period t ,
 208 where the flow of pollution in period t is Z_t and where Ψ is the
 209 pollution-decay parameter. Note that if $\Psi = 1$, then only current-period pollution
 210 matters. For simplicity, we normalize the initial stock of pollution to 0; thus,
 211 $\mathbb{Z}_1 = Z_1$. In addition, we assume that policy makers know the period t social cost
 212 of pollution, $C(\mathbb{Z}_t) = \xi \cdot \mathbb{Z}_t^2$ for $\xi \geq 0$.

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

$$W_t = CS_t + PS_t - C(Z_t). \quad (4)$$

216 **III. The Two-Party Two-Period Game**

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

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

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

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

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

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

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

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

246 This structure mimics, for instance, the response of U.S. power plants to
 247 the EPA's proposal to limit emissions of coal-fired plants to 1,100 pounds of CO₂
 248 per megawatt hour. If such proposed regulation is enacted, then coal-fired power
 249 plants would either invest in cleaner technologies (e.g., natural gas-fired boilers,
 250 carbon storage and capture technologies, co-generation with biomass) or retire the
 251 plant. On the other hand, natural gas-fired plants continue to produce electricity
 252 using their existing technologies.

253 **IV. The Optimal Dynamic Tax**

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

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

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

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

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

$$261 \quad R^{A,1} \equiv \{(\beta, x) \mid \{0 \leq \pi_1^\tau\} \cup \{0 \leq \pi_2^\tau\} \cup \{0 \leq \pi_0^\tau\}, 0 \leq \beta \leq \bar{\beta}, 0 \leq x \leq p\}.$$

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

271 How does policy affect the survival and modification regions and thus
 272 aggregate pollution? Recall that the pollution-production coefficient of units that
 273 adopted the cleaner technology is $\beta^m = (1 - \gamma)\beta$. Then, let $\Delta Z_1 = Z_1|_{\tau_1=0} -$
 274 $Z_1|_{\tau_1=\tau_{A,1}}$ denote the reduction of flow of pollution in period 1 (where $Z_1|_{\tau_1=0}$
 275 denotes pollution assuming no regulation, and $Z_1|_{\tau_1=\tau_{A,1}}$ denotes pollution
 276 assuming first-period tax of $\tau_{A,1}$); that is,

$$277 \quad \Delta Z_1 = \gamma \cdot \int \int_{R^{m,1}} \beta \cdot g(\beta, x) d\beta dx + \int \int_{R^0 - R^{A,1}} \beta \cdot g(\beta, x) d\beta dx.$$

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

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

$$291 \quad \tau_{A,1} = (2\xi\mathbb{Z}_{A,1} - \delta(1 - \Psi)(\alpha 2\xi\mathbb{Z}_{A,2} - (1 - \alpha)2\xi\mathbb{Z}_{B,2})) + \delta(1 - \alpha)2\xi\mathbb{Z}_{B,2}$$

$$292 \quad \tau_{A,2} = 2\xi\mathbb{Z}_{A,2}$$

$$293 \quad \tau_{B,2} = 0$$

294 **Proof:** The proof is in Appendix A.

295 The optimal dynamic tax $\tau_{A,1}$ is the outcome of current-period pollution
 296 (*the static Pigovian tax effect: $2\xi\mathbb{Z}_{A,1}$*), pollution being a stock and thus affecting
 297 the next period (*the pollution stock effect: $\delta(1 - \Psi)2\xi(\alpha\mathbb{Z}_{A,2}$*
 298 *$(1 - \alpha)\mathbb{Z}_{B,2})$*) and uncertainty regarding the future (*the political uncertainty*
 299 *effect: $\delta(1 - \alpha)2\xi\mathbb{Z}_{B,2}$*). On the other hand, the Pigovian tax denoted $\tau_{A,1}^{Pigou}$
 300 equals the difference between the marginal private cost and the social cost

301 calculated at the optimal solution; that is, $\tau_{A,1}^{Pigou} = 2\xi\mathbb{Z}_{A,1}$
 302 $\delta(1 - \Psi)(\alpha 2\xi\mathbb{Z}_{A,2} + (1 - \alpha)2\xi\mathbb{Z}_{B,2})$. Proposition 1, then, leads to the
 303 following:

304 (a) Proposition 1 suggests that the dynamic Pigovian tax may not be the
 305 optimal tax from a political economic perspective, even when the number
 306 of producers and consumers is large.² Given political uncertainty (i.e.,
 307 $\alpha < 1$) and $\delta > 0$, in equilibrium, Party A sets a higher pollution tax than
 308 the dynamic Pigovian tax; that is, $\tau_{A,1} > \tau_{A,1}^{Pigou}$.

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

310 i. The first-period tax equals the dynamic Pigovian tax; that is,
 311 $\tau_{A,1} = \tau_{A,1}^{Pigou}$.

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

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

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.

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

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

331 **V. An Upper Bound on Pollution**

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

337 Technically, let $\theta_{j,i}$ denote the intensity upper bound set by Party j in
 338 period i for $j \in \{A, B\}$ and $i \in \{1, 2\}$. We also modify Eq. (1) to include an upper
 339 bound on pollution per unit of output and denote production units' quasi-rents as
 340 π^θ . Using the definition of production units' quasi-rents, we transition from the
 341 micro to the macro level. Technically, a unit remains active if $\beta \in [0, \theta_{A,1}]$ and
 342 $\pi^\theta \geq 0$, and a unit adopts clean technology in the first period if $\beta \in$
 343 $(\theta_{A,1}, \theta_{A,1}/(1 - \gamma)]$ and expected quasi-rents are not negative. Otherwise, a unit
 344 becomes idle. Similarly, we can describe second-period survival and modification
 345 regions.

346 Monetary charges that equal the marginal social damage result in Pareto

347 optimality. However, estimating the social damage function is challenging
 348 (Baumol and Oates, 1971). An alternative cost-efficient approach introduced in
 349 the literature, assumes policy is set to achieve a predetermined aggregate pollution
 350 level. Building on this alternative approach, we assumed that at the beginning of
 351 the game Party A chooses the per-period expected aggregate level of pollution \bar{Z}
 352 (e.g., stock of pollution should not result in global average temperatures
 353 increasing by more than 2⁰C of their pre-industrial level), and then period 1
 354 begins and Party A sets policy. Furthermore, assume the intensity upper bound is
 355 set at the beginning of each period: $\theta_{A,1}$ for the first period and $\theta_{A,2}$ for the
 356 second. Note that although pollution is constrained by a predetermined aggregate
 357 level in period 1 (i.e., $Z_{A,1} \leq \bar{Z}$), political uncertainty results in policy containing
 358 only the expected value of the pollution stock in period 2 (i.e., $\alpha Z_{A,2} +$
 359 $(1 - \alpha)Z_{B,2} \leq \bar{Z}$). Formally, the Lagrangian of Party A's period 1
 360 constraint-maximization problem is

$$\begin{aligned}
 361 \quad \mathcal{L}_1 = & W_{A,1} + \delta(\alpha W_{A,2} + (1 - \alpha)W_{B,2}) + \lambda_1(Z_{A,1} - \bar{Z}) \\
 362 & + \lambda_2(\alpha Z_{A,2} + (1 - \alpha)Z_{B,2} - \bar{Z})
 \end{aligned}$$

363 where $0 < \lambda_1, \lambda_2$ are the Kuhn-Tucker multipliers. Party A sets $\theta_{A,1}$ and, if
 364 elected in period 2, sets $\theta_{A,2}$. In period 2, it chooses an intensity upper bound
 365 $\theta_{A,2}$ that maximizes Eq. (6) subject to $Z_{A,2} \leq \bar{Z}$. The Lagrangian of Party A's
 366 period 2 constraint-maximization problem is

$$367 \quad \mathcal{L}_2 = W_{A,2} + \mu(Z_{A,2} - \bar{Z})$$

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

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

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

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

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

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

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

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

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

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

$$405 \quad g(\beta, x) = A\beta^{\varphi_1-1}x^{\varphi_2-1} \text{ for } A, \varphi_1, \varphi_2 > 0.$$

406 This functional form suggests that when $\varphi_1 = 1$ and $\varphi_2 = 1$, the density
407 function is a uniform distribution function where $g(\beta, x) = A$ for $\{\beta, x\} \mid 0 \leq$
408 $\beta \leq \bar{\beta}, 0 \leq x \leq \bar{x}\}$ and 0 otherwise. However, when $\varphi_1 < 1$ ($\varphi_2 < 1$), the
409 density function places more weight on the low-polluting (efficient) production
410 units. However, if $\varphi_1 > 1$ ($\varphi_2 > 1$), then the density function places more
411 weight on the high-polluting (inefficient) units.

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

416 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
A	2115.3	φ_1	2.0	φ_2	2.0
$p_{A,1}$	10.34	$p_{A,2}$	10.34	$p_{B,2}$	10.34
I_1^m	1.5982	I_2^m	0.79909	ω	1/2
δ	0.95	α	0.55	γ	0.5
ρ	0.05	ξ	$9.8 * 10^{-5}$	$\bar{\beta}$	1
Ψ	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

³ Data are available at <http://www.eia.gov/electricity/data/browser/>

431 assumed to generate one unit of output, which in the calibration is equivalent to
 432 70,750 megawatts), with pollution flow of 37,390 units (using Eq. (2) and the
 433 definition of Z^0). Assuming the power utility sector is producing 30% of annual
 434 greenhouse gases produced in the U.S., and given that the U.S. generated about
 435 6,500 million tons of CO₂ in 2012,⁴ the result is 0.05 million tons of CO₂ per
 436 pollution unit ($= 6500 \cdot 0.3/37390$).

437 In what follows, assume predetermined pollution stock in period 1 of
 438 20,158 units (a reduction of 46.5% in the pollution level). This level of pollution
 439 is compatible with an intensity standard of $\theta_{A,1} = 0.43759$ and $\theta_{A,2} =$
 440 0.39591 and with an optimal (dynamic) tax of $\tau_{A,1} = 6.58$ and $\tau_{A,2} = 3.95$
 441 per pollution unit. Because of political uncertainty and pollution not being a flow,
 442 the dynamic Pigovian tax of period 1 is smaller than the optimal dynamic tax; that
 443 is, the dynamic Pigovian tax is $4.89 < 6.58 = \tau_{A,1}$.

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

447 *A. The Tax Regime*

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

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

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

and their intercepts are $x(\beta = 0, \tilde{\pi}_0^T = 0) = 10.3400 > x(\beta = 0, \tilde{\pi}_2^T = 0) = 10.1259 > x(\beta = 0, \tilde{\pi}_1^T = 0) = 9.0671$. We depict $\tilde{\pi}_i^T$ for $i \in \{0, 1, 2\}$ in Figure 1, and note that DCBEO is the survival region $R^{A,1}$. The tax policy results in inefficient and dirty units exiting the industry (i.e., units located in region $R^0 - R^{A,1}$). 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

466 from the late adopters and identify units that do not adopt the technology in either
 467 period 1 or period 2 (see Appendix B):

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

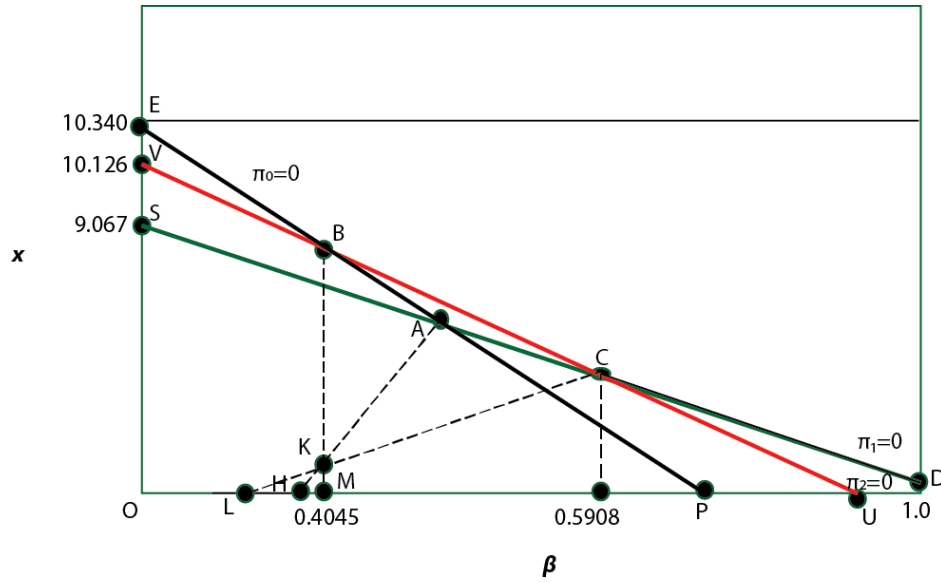
$$x_{0,1} = 44.3222 \cdot \beta - 16.3915 \quad (10)$$

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

$$x_{1,2} = 33.7355 \cdot \beta - 12.1092 \quad (11)$$

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

$$\beta = 0.4045 \quad (12)$$



471
 472 *Figure 1. First-period survival region under a tax.*

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

476 These are the efficient yet polluting units.

477 However, if Party A is reelected, then some of the units that did not adopt
478 the clean technology in the first period may adopt it in the second period. The late
479 adopters are less efficient but less polluting units than the early adopters. The late
480 adopters purchase the clean technology only if Party A is reelected, and they
481 make the purchase at a lower upfront cost than the early adopters (recall that $\rho =$
482 0 in period 2, but that $\rho > 0$ in period 1 and that $I_2^m = (1 - \omega)I_1^m$ for $\omega =$
483 $0.5 > 0$). In the numerical model, 21,290 production units (i.e., power plants)
484 adopt the clean technology in period 1, while 171,480 production units are active.
485 In the second period, because investment is irreversible, the number of active
486 units does not change. However, the number of active units that adopt the cleaner
487 technology increases by 10,580 units. Note that although more output is produced
488 via a tax in period 2 (see Table 3), more people are employed under a standard
489 (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%

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

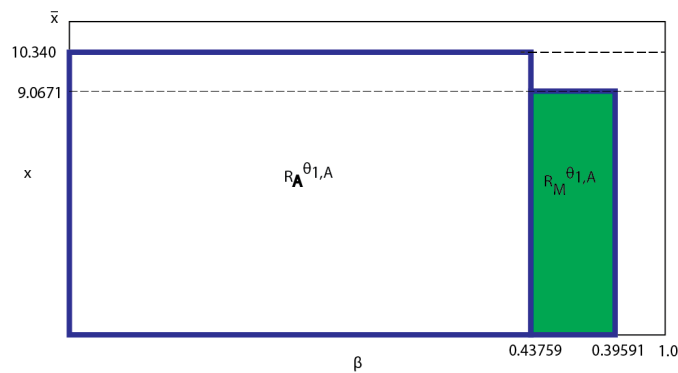
491 *B. Adoption and the emission upper bound*

492 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 $R_A^{\theta_{A,1}}$ 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, $R^{\theta_{A,1}} = R_M^{\theta_{A,1}} \cup R_A^{\theta_{A,1}}$ (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.



511

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

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

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

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

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

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

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

550 Returning to our real-world example, EPA emission control policies
551 became progressively more stringent after their introduction in the early 1970s.
552 From 1975 to 2014, light vehicles' average CO₂ grams per mile declined by about
553 50% while miles per gallon increased by more than 100%.⁵

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

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

585 more adoption and thus solidifies the transition toward clean technologies more
586 than a tax. It is interesting that although economists argue for the use of price
587 instruments, politicians are much keener to employ an intensity upper bound, as
588 the examples in the introduction suggest.

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

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

609 Capital-intensive industries (e.g., power plants) are the main source of
610 anthropogenic emissions. These industries make large capital investments and are

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

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

References

- Acemoglu, D., & Robinson, J. A. (2001). Inefficient redistribution. *American Political Science Review*, 95(3): 649–661.
- Aghion, P., & Bolton, P. (1990). Government domestic debt and the risk of default: A political-economic model of the strategic role of debt. In *Public debt management: Theory and history*. R. Dornbusch & M. Draghi. (Eds.) Cambridge University Press. pp. 315–349.
- Arrow, K. J. (1962). The economic implications of learning by doing. *Review of Economic Studies*, 29(3): 155–173.
- Ashford, N.A., Ayers, C., Stone, R.F. (1985). Using regulation to change the market for innovation. *Harvard Environmental Law Review*, 9: 419–467.
- Azzimonti, M. (2011). Barriers to investment in polarized societies. *American Economic Review*, 101(5): 2182–2204.
- Babcock, B. A., P. G. Lakshminarayan, J. J. Wu, & D. Zilberman. (1997). Targeting tools for the purchase of environmental amenities. *Land Economics*, 73(3): 325–339
- Bansal, S., & Gangopadhyay, S. (2005). Incentives for technological development: BAT is bad. *Environmental & Resource Economics*, 30: 345–367.
- Baumol, W. J., & Oates, W. E. (1971). The Use of Standards and Prices for Protection of the Environment. *The Swedish Journal of Economics*, 73: 42–54.
- Baumol, W. J., & Oates, W. E. (1988). *The theory of environmental policy*. Cambridge, MA: Cambridge University Press
- Berck, P. & Helfand, G. (1990). Reconciling the von Liebig and differentiable crop production functions. *American Journal of Agricultural Economics*, 72(4): 985–996
- Bohn, F. (2007). Polarisation, uncertainty and public investment failure. *European Journal of Political Economy*, 23(4): 1077–1087.
- Buchanan, J. M. & Tullock, G. (1975). Polluters' profits and political response: Direct controls versus Taxes. *The American Economic Review*, 65(1): 139–147.
- Calvo, G. (1978). On the time consistency of optimal policy in a monetary economy. *Econometrica*, 6: 1411–1428.
- Caparros, A., Just, R., & Zilberman, D. (2015). Dynamic Relative Standards versus Emission Taxes in a Putty-Clay Model. *Journal of the Association of Environmental and Resource Economists*, 2(2): 277–308
- Chaney, T. (2008). Distorted gravity: The intensive and extensive margins of international trade. *American Economic Review*, 98(4): 1707–1721.
- Dasgupta, A. K. (1970). Some problems of estimating the long-run marginal costs of electricity a vintage capital approach. *Economics of Planning*, 10(3): 193–220
- Fischer, S. (1980). Dynamic inconsistency, cooperation and the benevolent dissembling government. *Journal of Economic Dynamics and Control*, 2: 93–107
- Fuss, M. (1978). Factor substitution in electricity generation: A test of the putty clay hypothesis In *Production economics: A dual approach to theory and applications, Vol. 2 of History of Economic Thought Chapters*. M. Fuss & D. McFadden (Eds.) Amsterdam and Holland: North-Holland Publishing Co. pp. 187–214.
- Gerard, D., & Lave, L.B. (2005). Implementing technology-forcing policies: The 1970 Clean Air Act amendments and the introduction of advanced automotive emissions controls in the United States. *Technological Forecasting and Social Change*, 72: 761–778.
- Grossman, G., & Helpman, E. (2001). *Special interest politics*. Cambridge, MA: MIT Press.
- Helpman, E., Melitz, M., & Rubinstein, Y. (2008). Estimating trade flows: Trading partners and trading volumes. *Quarterly Journal of Economics*, 123(2): 441–487.

- Hochman, E., & Zilberman, D. (1978). Examination of environmental policies using production and pollution microparameter distributions. *Econometrica*, 46(4): 739-760.
- Houthakker, H. S. (1955). The Pareto distribution and the Cobb-Douglas production function in activity analysis. *Review of Economic Studies*, 23:27-31.
- Gunther, H., & Diamond, L. (2003). Species of Political Parties: A new typology. *Party Politics*, 9(2): 167-199
- Jaffe, A.B., Newell, R.G., & Stavins, R.N. (2002). Environmental policy and technological change. *Environmental and Resource Economics*, 22(1-2): 41-71.
- Johansen, L. (1972). An integration of micro and macro, short run and long run aspects. Contribution to Economic Analysis 75, Amsterdam and Holland: North-Holland Publishing Co.
- Kemp, R. (1997). Environmental policy and technical change: A comparison of the technological impact of policy instruments. Brookfield, VT: Edward Elgar Publishing Company.
- Khanna, M., & Rao, N. D.. (2009). Supply and demand of electricity in the developing world. In *Annual Review of Resource Economics*, Vol. 1, G. Rausser, K. Smith, & D. Zilberman, (Eds.) Annual Reviews: Palo Alto, California
- Kydland, F. E., & Prescott, E.C. (1977). Rules rather than discretion: The inconsistency of optimal plans. *Journal of Political Economy*, 3: 473-492.
- Laffont, J. J., & Tirole, J. (1996a). Pollution permits and compliance strategies. *Journal of Public Economics*, 62(1-2): 85-125
- Laffont, J. J., & Tirole, J. (1996b). Pollution permits and environmental innovation. *Journal of Public Economics*, 62(1-2): 127-140
- Lee, J., Veloso, F.M., Hounshell, D.A., & Rubin, E.S. (2010). Forcing technological change: A case of automobile emissions control technology development in the US. *Technovation*, 30(4): 249-264.
- Lutz, S., Lyon, T.P., & Maxwell, J.W. (2000). Quality leadership when regulatory standards are forthcoming. *Journal of Industrial Economics*, XLVIII(3): 331-348.
- McFarland, M. (1992). Investigations of the environmental acceptability of fluorocarbon alternatives to chlorofluorocarbons. Proceedings of the National Academy of Sciences of the United States of America.
- Melitz, M.J., & Ottaviano, G.I.P. (2008). Market size, trade, and productivity. *Review of Economic Studies*, 75(1): 295-316.
- Mickwitz, P., Hyvattinen, H., & Kivimaa, P. (2008). The role of policy instruments in the innovation and diffusion of environmentally friendlier technologies: Popular claims versus case study experiences. *Journal of Cleaner Production*, 16(S1): S162-S170.
- Miller, A.S. (1995). Environmental regulation, technological innovation, and technology-forcing. *Natural Resources and Environment*, 10(2): 64-69.
- Millner, A. (2013). Policy distortions due to heterogeneous beliefs: Some speculative consequences for environmental policy. In *Political economy and instruments of environmental politics*. A. Kollmann, J. Reichl, & F. Schneider (Eds.). CESifo seminar series
- Moffitt, L. J., Zilberman, D., & Just, R. E. (1978). "A 'putty clay' approach to aggregation of production / pollution possibilities: An application in dairy waste control." *American Journal of Agricultural Economics*, 60(3): 452-459
- Mohr, R.D. (2006). Environmental performance standards and the adoption of technology. *Ecological Economics*, 58: 238-248.
- Nordhaus, W.D. (2009). The perils of the learning model for modeling endogenous technological change. National Bureau of Economic Research Working Paper #14638. <http://www.nber.org/papers/w14638>
- Paris, Q. (1990). "The Vonliebig hypothesis." *American Journal of Agricultural Economics*, 77(4): 1019-1028
- Persson, T., & Svensson, L. E. O. (1989). Why a stubborn conservative would run a deficit: Policy with time-inconsistent preferences. *Quarterly Journal of Economics*, 104(2): 325-345.

- Persson, T., & Tabellini, G. (1999). The size and scope of government: Comparative politics with rational politicians. *European Economic Review*, 43(4–6): 699–735.
- Persson, T., & Tabellini, G. E. (2000). *Political economics: Explaining economic policy*. Cambridge, MA: MIT Press.
- Pigou, A.C. (1932). *The economics of welfare*. London, UK: Macmillan
- Popp, D. (2003). Pollution control innovations and the Clean Air Act of 1990. *Journal of Policy Analysis and Management*, 22(4): 641–660.
- Puller, S. L. (2006). The strategic use of innovation to influence regulatory standards. *Journal of Environmental Economics and Management*, 52(3): 690–706.
- Rausser, G. C., Swinnen, J., & Zusman, P. (2011). *Political power and economic policy: Theory, analysis, and empirical applications*. Cambridge University Press.
- Sunding, D. & Zilberman, D. (2001). The agricultural innovation process: Research and technology adoption in a changing agricultural sector. In *Handbook of agricultural economics*, B. L. Gardner & G. C. Rausser, (Eds.) Vol. 1, Elsevier, chapter 4, pp. 207–261
- Tabellini, G., & Alesina, A. (1990). Voting on the budget deficit. *American Economic Review*, 80(1): 37–49.
- Taylor, M.R., Rubin, E.S., & Hounshell, D.A. (2005). Control of SO₂ emissions from power plants: A case of induced technological innovation in the US. *Technological Forecasting and Social Change*, 72: 697–718.
- Weitzman, M. L. (1974). Prices vs. quantities. *Review of Economic Studies*, 41(4): 477–491.
- Wu, J. J., Zilberman, D., & Babcock, B. A. (2001). Environmental and distributional impacts of conservation targeting strategies. *Journal of Environmental Economics and Management*, 41 (3): 333–350

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

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

where $\bar{X}(\beta) \equiv \max\{\bar{x}_0(\beta), \bar{x}_1(\beta), \bar{x}_2(\beta)\}$, and the following curves define $\bar{\beta}$, $\bar{x}_0(\beta)$, $\bar{x}_1(\beta)$, and $\bar{x}_2(\beta)$:

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

$$2) \pi_0^{\tau,1}(\beta, x) = 0 \Rightarrow \bar{x}_0(\beta) \text{ (i.e., line EP in Figure 1): } \bar{x}_0(\beta) = \frac{P-T \cdot \beta}{(1+\delta)}$$

$$3) \pi_1^{\tau,1}(\beta, x) = 0 \Rightarrow \bar{x}_1(\beta) \text{ (i.e., line SD in Figure 1): } \bar{x}_1(\beta) = \frac{P-T \cdot (1-\gamma) \cdot \beta - I_1^m}{(1+\rho)(1+\delta)}$$

$$4) \pi_2^{\tau,1}(\beta, x) = 0 \Rightarrow \bar{x}_2(\beta) \text{ (i.e., line VU in Figure 1): } \bar{x}_2(\beta) = \frac{P-T \cdot \beta - \delta \cdot \alpha \cdot (I_2^m - \tau_{A,2} \cdot \gamma \cdot \beta)}{(1+\delta)}.$$

Note that the set $\left\{ \{\beta, x\} \mid \beta \in [0, \bar{\beta}], x = \max\{\bar{x}_0(\beta), \bar{x}_1(\beta), \bar{x}_2(\beta)\} \right\}$ defines the line EBCD in Figure 1.

II) The *second-period survival region* is

$$R_{A,2} = \left\{ \{\beta, x\} \mid 0 \leq \beta \leq \min\{\bar{\beta}, \check{\beta}\}, 0 \leq x \leq \min\{\bar{X}, \check{X}\} \right\}$$

where $\check{X} \equiv \max\{\check{x}_0(\beta), \check{x}_1(\beta), \check{x}_2(\beta)\}$, and the values $\check{\beta}$, $\check{x}_0(\beta)$, $\check{x}_1(\beta)$, $\check{x}_2(\beta)$ are defined

as follows:

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

$$2) \pi_0^{\tau,2}(\beta, x) = 0 \Rightarrow \widetilde{x}_0 = p_{A,2} - \tau_{A,2} \cdot \beta$$

$$3) \pi_1^{\tau,2}(\beta, x) = 0 \Rightarrow \widetilde{x}_1 = \frac{p_{A,2} - \tau_{A,2} \cdot (1-\gamma) \cdot \beta}{(1+\rho)}$$

$$4) \pi_2^{\tau,2}(\beta, x) = 0 \Rightarrow \widetilde{x}_2 = p_{A,2} - \tau_{A,2} \cdot (1-\gamma) \cdot \beta - I_2^m$$

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 Conditions (F.O.C.) of this maximization problem is

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

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

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

(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

$$\tau_{A,1} = 2\xi \mathbb{Z}_{A,1} + \underbrace{\frac{\delta(1 - \Psi)2\xi(\alpha \mathbb{Z}_{A,2} - (1 - \alpha)\mathbb{Z}_{B,2})}{}}_{\text{The stock effect}} + \underbrace{\frac{\delta(1 - \alpha)2\xi \mathbb{Z}_{B,2}}{}}_{\text{The political uncertainty effect}}$$

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 equilibrium 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 $\pi_1^\tau = \pi_0^\tau$):

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

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

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

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

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

Q.E.D.