The Tradeoff Between Employment and Environment

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Abstract

Often welfare-maximizing environmental policies are politically infeasible because of job loss. This paper answers whether politically feasible environmental policies exist, and if yes, how these policies look like. We construct a search equilibrium model featuring multiple sectors and endogenous emission decisions along extensive and intensive margins. We analytically show that a class of policies that impose a higher flow cost in the polluting sector without increasing emission along its intensive margin is no more politically feasible than a laissez-faire equilibrium, and vice versa. This broad class of policies includes simple emission taxes and intensity standards, explaining the non-stop lobbying in the process of environmental lawmaking. We characterize a tax-revenue-recycling method and an empirically testable condition under which revenue-neutral emission taxes could be politically feasible and reap a double dividend: while a Pigouvian tax on emission corrects production externality, the rebate of the tax revenues internalizes job allocation externality in the labor market.

Keywords: Unemployment; Environmental Lawmaking; Double Dividend.

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1 Introduction

Pollution raises global concerns, giving rise to the formation of international environmental agreements such as the Kyoto Protocol (Nordhaus, 2006; Açıkgöz and Benchekroun, 2017; Harrison and Lagunoff, 2017). Nevertheless, environmental policies may result in job loss (Greenstone, 2002; Walker, 2013; Yip, 2018). The fear of this unemployment effect may create domestic political forces lobbying against environmental lawmaking, making these policies "politically infeasible".[1] To understand the politics behind the formulation of environmental policies, this paper answers three questions: (i) whether standard environmental policies could improve environmental quality without increasing involuntary unemployment, (ii) if yes, how these policies look like, and (iii) whether they are welfare-improving.

Answering these questions contributes to a broad literature on the welfare analysis in environmental economics. This literature has provided guidance of policy choices to correct externality and to maximize social welfare. However, "*existing institutions do not stack up at all well in terms of these guidelines*" (Oates and Portney, 2003). We consider constraints of political feasibility in reality: policymakers are constrained to vote down policies that expect to raise the level of unemployment or deteriorate the environmental quality compared to the status quo. These constraints are realistic: recent studies suggest that a majority may prefer a policy instrument different than what a social planner would choose (Alesina and Passarelli, 2014). Welfare-maximizing policies may not be politically feasible; we seek welfare-improving policies that respect the political feasibility constraint. Hence, policies recommended by our analysis are politically feasible and thus more practical and relevant to realities.

We answer the three questions via a search equilibrium model featuring multiple sectors and endogenous emission decisions along extensive and intensive margins. Our analytically tractable model, hence, complements a series of influential papers by Bovenberg and van der Ploeg that study the unemployment effects of environmental policies. This paper differs from Bovenberg and van der Ploeg (1996) and Bovenberg and van der Ploeg (1998a) by modeling the underlying labor market imperfection that leads to involuntary unemployment. Bovenberg and van der Ploeg (1998b), integrating frictional unemployment, study the unemployment effects of environmental tax. While these models, with only one formal sector, abstract sectoral reallocation, our model features multiple sectors, allowing nonpolluting sectors to absorb unemployed workers from polluting sectors. This mechanism is shown to be important in the analyses on the unemployment effect of environmental policies (Wagner, 2005; Walker, 2013; Hafstead and Williams III, 2018).

[1] Throughout this section, a policy is considered politically feasible if it does not raise the level of unemployment or deteriorate environmental quality compared to the status quo. A policy is considered more politically feasible than another policy if the former policy yields unemployment and environmental quality no worse than the other one. We will mathematically define political feasibility in Section 3.

Our model also incorporates all the margins of environmental policies considered in the literature: the intensive margin (the level of emission per production unit), the extensive margin (allocation between polluting and nonpolluting sectors), and the scale effect (the scale of output). In some previous studies (Carraro et al., 1996; Bye, 2002), the intensive margin of emission is assumed to be fixed, which can be interpreted as a short-term technological constraint. Nevertheless, this margin is found to be empirically important for emission control (Shapiro and Walker, 2018). Meanwhile, the extensive margin is the driving force for job loss at the introduction of environmental policies (Walker, 2011). We therefore allow adjustment on emission decisions along both margins.

This paper analyzes two broad classes of policies. The first class increases the flow cost of production in the polluting sector without increasing emission along its intensive margin such as a lump-sum tax on polluting firms, a simple per-unit emission tax, and an intensity standard. The second class affects the flow cost in both polluting and nonpolluting sectors including a revenue-neutral emission tax scheme that levies a per-unit emission tax on firms in the polluting sector and rebates the tax revenue to firms in the two sectors. Using the criteria of political feasibility, our analyses compare (i) among policies in the first class and (ii) between the first and the second classes. Our analysis yields five remarkable results.

First, the tradeoff between unemployment and the extensive margin of emission is inevitable in the first class of policies. A higher flow cost of production in the polluting sector reduces the value and thus the supply of their vacancies. This direct effect raises unemployment and reduces the market share of the polluting sector, leading to the tradeoff. The expansion of the market share of the nonpolluting sector lowers the relative price of their products, depressing the supply of their vacancies. This general equilibrium further increases unemployment. This result highlights the importance of having multiple sectors in modeling the tradeoff between employment and environmental quality.

Second, polices in the first class and the laissez-faire equilibrium may not be more politically feasible than each other. None of the policies in the first class is politically feasible because of the higher unemployment rate. The laissez-faire equilibrium is not more politically feasible than those policies in the first class because of the lower environmental quality. While local environmental organization lobbies against the laissez-faire equilibrium, polluting industries and labor unions lobby against environmental policies in this class. Lobbying continues because neither policy in the first class nor the laissez-faire equilibrium is more politically feasible than the other. Our result lays the theoretical foundation of the conflicts between the two lobbying groups in the literature on the political economy of environmental policies (Aidt, 1998; Fredriksson and Svensson, 2003; Oates and Portney, 2003; List and Sturm, 2006).

Third, there always exist intensity standards that are more politically feasible than a simple per-unit emission tax, and not vice versa. Without paying an emission tax, intensity standards incur a lower flow cost than simple emission taxes to achieve the same amount of emission abatement on the firm level. Hence, given any emission tax rate, there always exists an interval of intensity standard that leads to a lower unemployment rate and a better environmental quality than the emission tax. Nevertheless, given any intensity standard, we find no emission tax rate that is more politically feasible than the intensity standard. While taxes are generally first-best, our finding complements the literature (Gerlagh and Van der Zwaan, 2006; Fischer and Springborn, 2011; Li and Shi, 2011; Holland, 2012; Parry and Williams III, 2012; Tombe and Winter, 2015) by highlighting that the political concern is one of the factors favoring an intensity standard over an emission tax.

Fourth, we pin down an empirically testable condition under which there exists a revenue-neutral emission tax scheme that is politically feasible. A Pigouvian tax on emission reduces emission along the intensive margin. An increased flow cost on polluting firms raises the unemployment rate and reduces the market share of the polluting sector (emission along the extensive margin). Hence, the environmental quality is improved along both margins. The expansion of the nonpolluting sector makes clean goods relatively more abundant, thereby reducing the price of clean goods and thus the revenue in the nonpolluting sector. We show that if the elasticity of revenue with respect to its market share is small enough in the nonpolluting sector, the negative general equilibrium effect on their revenue and thus profit can be outweighed by the direct impact of the rebate. Consequently, the revenue-neutral emission tax scheme could reduce both unemployment and emission and is thus politically feasible.

The condition is testable ex ante so that policymakers could verify whether a politically feasible revenue-neutral emission tax scheme exists prior to the implementation of the policy. Moreover, the condition requires only a few sufficient statistics (i.e., the respective elasticity of revenue with respect to the market share in each sector) which are easily acquired without solving a structural model. Furthermore, these revenue-neutral emission tax schemes are shown to be more politically feasible than any per-unit emission tax and a certain interval of intensity standard.

Fifth, we propose a tax-revenue-recycling method under which a revenue-neutral emission tax scheme is welfare-improving. In environmental economics, deadweight loss is created by production externality. The creation of vacancies of each type indeed creates another externality, job allocation externality, in the labor market. For example, the creation of a vacancy in the polluting sector expands its market share and reduces the relative price and thus the revenue of each existing firm in this sector. Meanwhile, its creation shrinks the nonpolluting sector and increases the revenue of all existing firms in the nonpolluting sector. Our proposal therefore reaps a double dividend: while a Pigouvian tax on emission corrects the production externality, the rebate of the tax revenues internalizes the job allocation externality in the labor market. The second dividend differs from the reduction in the distortion cost of the preexisting tax, suggested in the literature on the double-dividend of a revenue-neutral emission tax scheme (Goulder, 1995; Parry and Bento, 2000; Chiroleu-

Assouline and Fodha, 2006; Bento and Jacobsen, 2007; Chiroleu-Assouline and Fodha, 2014; Gahvari, 2014).

The rest of the paper is organized as follows. Section 2 presents the structure of the model. Section 3 introduces the environmental policy selection criterion used in this paper. Section 4 compares environmental policies using the proposed criterion. Section 5 performs a conventional welfare analysis of the considered policies. Section 6 concludes.

2 The Basic Model

This section constructs a simple search equilibrium model featuring (i) involuntary unemployment and (ii) extensive and intensive margins of emission, all of which are endogenized. The model provides major mechanisms through which policies affect the tradeoff between employment (i.e., frictional unemployment) and environmental quality (the emissions along the two margins).

Time is continuous. There is a continuum of utility-maximizing workers and profit-maximizing firms. Both workers and firms are risk-neutral and discount the future with an identical real interest rate r.[2] Workers are identical and live infinitely. Without loss of generality, we normalize the measure of workers to unity.

2.1 Technology

To produce the final good, the economy first uses labor and capital to produce two non-storable intermediate goods, sells them in a competitive market, and then immediately transforms them into the final consumption good. The technology of production for the final good is

$$Y = \left(\alpha Y_d^{\rho} + (1-\alpha) Y_c^{\rho}\right)^{\frac{1}{\rho}}, \tag{1}$$

where Y_d is the aggregate production of the first input, Y_c is the aggregate production of the second input, $\rho < 1$, and $\alpha \in (0, 1)$. The production of Y_d will emit harmful substances

[2]This assumption is common in the literature (Mortensen and Pissarides, 1994; Moen, 1997; Moscarini, 2005; Rogerson et al., 2005; Gonzalez and Shi, 2010; Fujita and Ramey, 2012; Michaillat, 2012). Applications of the search and matching model also assume agents to be risk-averse, such as the literature that investigates the optimal unemployment benefits with search frictions (Fredriksson and Holmlund, 2006; Guerrieri et al., 2010). Recent literature also investigates job search behaviors with the preference of ambiguity aversion (Chan and Yip, 2018a). Our model can be easily extended to incorporate agents' ambiguity preferences; we do not do so because the modification of agents' preference towards ambiguity complicates our model without providing a richer economic intuition in our context.

that pollute the environment, and the production of Y_c does not pollute the environment.[3] The subscript d denotes "dirty", and the subscript c denotes "clean". We call Y_d the dirty good and Y_c the clean good. The elasticity of substitution between the dirty good and the clean good is $1/(1-\rho)$. α is a parameter for the relative importance of the dirty good. Equation (1) allows us to interpret the final consumption good as a utility index defined over the two intermediate goods. Throughout the paper, we will normalize the price of the final good to unity.

Since the markets for the two intermediate goods are competitive, the prices of the intermediate goods are

$$p_d = \alpha \left(\frac{Y}{Y_d}\right)^{1-\rho} \text{ and } p_c = (1-\alpha)\left(\frac{Y}{Y_c}\right)^{1-\rho}. \tag{2}$$

The technology of production for the intermediate goods is Leontief. When matched with a firm with the necessary equipment, a worker produces A units of the respective good. $A > 0$ is a parameter that measures productivity. The necessary equipment is sector-specific: a vacancy for producing intermediate good j, once it is created, cannot be used to produce the other intermediate good.

2.2 Search and Match in the Labor Market

We assume that workers are either employed or unemployed. Only unemployed workers search. Firms can choose to create either a vacancy for producing the dirty good or a vacancy for producing the clean good. The capital cost k is incurred before the firm creates a vacancy. A firm must decide which good to produce before it creates a vacancy. There is free entry into both dirty-good and clean-good vacancies. At any point in time, a worker can work on only one job, and a vacancy can only be filled by one worker.

Search is undirected. Thus, both types of vacancies have the same probability of meeting workers. Firms and workers come together via a matching technology $M(u, v)$ where u is the unemployment rate, and v is the vacancy rate (the total number of vacancies). We make the standard assumptions in the literature: $M(u, v)$ is twice differentiable, increasing in both arguments, has constant returns to scale, and satisfies the standard Inada-type assumptions. Thus, the flow rate of match for a vacancy is $M(u, v)/v \equiv q(\theta)$, where $q(\cdot)$ is a differentiable decreasing function, and $\theta \equiv v/u$ is the tightness of the labor market. Thus, the flow rate of match for an unemployed worker is $M(u, v)/u = \theta q(\theta)$.[4]

[3] This simplification is adopted in the search and matching literature (Acemoglu, 2001; Chassamboulli and Palivos, 2014). A similar constant elasticity of substitution (CES) aggregation function is also used in Hafstead and Williams III (2018).

[4] Endogenizing search intensity in this model is simple but would not result in richer economic intuition. No results in this paper would be altered by endogenizing search intensity.

$\theta q(\theta)$ is increasing in θ, $\lim_{\theta\to 0} q(\theta) = \infty$, $\lim_{\theta\to\infty} q(\theta) = 0$, $\lim_{\theta\to 0}\theta q(\theta) = 0$, and $\lim_{\theta\to\infty}\theta q(\theta) = \infty$. Finally, all filled jobs end with the exogenous flow rate $\lambda > 0$.

Upon matching, the worker and the firm bargain on the wage for producing good j. After bargaining, production starts, the firm sells the product and pays wage to the worker.[5] The worker holds the job until the separation shock arrives. When the separation shock arrives, the worker becomes unemployed and goes back to search. The flow return from unemployment is z, where z can be interpreted as the level of utility derived from leisure or the value of home production.

2.3 Bellman Equations

Let J_j^E denote the value of employment on the job that produces good j and J^U the value of unemployment. w_j is the wage for producing good j. J_j^E can be written as

$$rJ_j^E = w_j + \lambda(J^U - J_j^E). \tag{3}$$

Denote the proportion of dirty-good vacancies among all vacancies as ϕ. J^U can be written as

$$rJ^U = z + \theta q(\theta)\Big[\phi(J_d^E - J^U) + (1-\phi)(J_c^E - J^U)\Big]. \tag{4}$$

Since both types of vacancies meet workers at the same rate in steady state, and workers accept both types of jobs in equilibrium, ϕ is also the share of dirty-good jobs among all filled jobs.

Let J_j^F denote the value of a filled job that produces good j, and J_j^V the value of a vacancy for producing good j. Let x denote the level of pollutant emission of each filled job producing the dirty good. Let $C(\bar{x} - x)$ denote the total cost of abating emission from $\bar{x}$ (the unabated level) to x (the abated level). Firms producing dirty goods choose the emission level x to maximize the asset value of a filled job. Hence, the asset value of a filled job producing good j is:

$$\begin{aligned} rJ_d^F &= \max_x \Big[p_d A - w_d - C(\bar{x} - x) + \lambda(J_d^V - J_d^F)\Big] \text{ and} \\ rJ_c^F &= p_c A - w_c + \lambda(J_c^V - J_c^F). \end{aligned} \tag{5}$$

We make the following assumptions on the cost function of abatement: $C : [0, \bar{x}] \longmapsto \mathbb{R}_+$

[5]The model assumes that workers are hired only for production and not for other activities such as recruitment. Readers who are interested in theoretical frameworks in which workers engage in recruitment are referred to Hafstead and Williams III (2018). Also, the key results of this paper remain unchanged regardless of the presence of payroll tax.

is twice differentiable, $C(0) = 0$, $C'(\cdot) > 0$, $C''(\cdot) > 0$, $\lim_{x \to \bar{x}} C'(\bar{x} - x) = 0$, and $\lim_{x \to 0} C'(\bar{x} - x) = \infty$. So, the greater is abatement level, the costlier is an additional unit of abatement. The optimal level of emission per dirty-good job x satisfies the following first-order condition:

$$C'(\bar{x} - x) = 0. \tag{6}$$

Given the assumptions on the cost function of abatement, the optimal emission level x is given by $\bar{x}$. While abatement is costly, it does not provide any economic benefit to dirty-good producers. As a result, they do not abate emission, and the abatement cost is $C(\bar{x} - x)$=0.

The asset value of a vacancy for producing good j is:

$$rJ_j^V = q(\theta)\left(J_j^F - J_j^V\right). \tag{7}$$

Due to search friction, at the moment a worker finds a job, there is a bilateral monopoly, and this leads to rent sharing over the surplus of the match. We assume that the rent sharing rule is:

$$(1 - \beta)(J_j^E - J^U) = \beta(J_j^F - J_j^V), \tag{8}$$

where $\beta \in (0, 1)$. This rule is the implication of Nash bargaining between risk-neutral workers and firms who have the same discount rate, where the worker has bargaining power β (Pissarides, 2000).[6]

The free entry and exit of vacancies drive the expected gross profits of vacancies to the machinery cost k; thus

$$J_j^V = k. \tag{9}$$

Finally, in steady state, flows out of unemployment are equal to the number of separations from jobs. Thus

$$u = \frac{\lambda}{\lambda + \theta q(\theta)}. \tag{10}$$

2.4 Steady-State Equilibrium

Definition 1. *A steady-state equilibrium is defined as* $\{Y, p_j, w_j, x, u, \phi, \theta, J_j^E, J^U, J_j^F, J_j^V\}$ *such that for all* $j \in \{c, d\}$,

1. *(Production of Final Goods):* Y *satisfies equation (1);*

[6] Chan and Yip (2018a) shows that this rule is also implied if workers and firms are ambiguity-averse.

2. *(Goods Market Clearing): Prices of two intermediate goods p_j satisfy equation (2);*

3. *(Value Functions): J_j^E, J^U, J_j^F, and J_j^V satisfy equations (3), (4), (5), and (7);*

4. *(Optimal Emission Level): Emission level x satisfies equation (6);*

5. *(Rent Sharing): Wages for the two jobs w_j satisfy the sharing rule (8);*

6. *(Free Entry and Exit): The proportion of dirty-good jobs ϕ and market tightness θ satisfy equation (9);*

7. *(Steady-State Accounting): The unemployment rate u satisfies equation (10).*

We characterize the equilibrium objects as functions of ϕ and θ. In a steady-state equilibrium, $Y_d = (1-u)\phi A$ and $Y_c = (1-u)(1-\phi)A$. Using equation (2), the prices are

$$\begin{aligned} p_d(\phi) &= \alpha \left\{ \frac{[\alpha\phi^\rho + (1-\alpha)(1-\phi)^\rho]^{\frac{1}{\rho}}}{\phi} \right\}^{1-\rho} \text{ and} \\ p_c(\phi) &= (1-\alpha) \left\{ \frac{[\alpha\phi^\rho + (1-\alpha)(1-\phi)^\rho]^{\frac{1}{\rho}}}{1-\phi} \right\}^{1-\rho}. \end{aligned} \tag{11}$$

p_d strictly decreases with ϕ, and p_c strictly increases with ϕ. In a steady-state equilibrium, $\phi = Y_d/(Y_d + Y_c)$ is the quantity share of dirty goods in the market. The increase in ϕ leads to an increase in the relativity quantity of the dirty goods, thus lowering its value.

From equations (3), (5), (8), and (9), the wage equations are

$$\begin{aligned} w_d &= (1-\beta) r J^U + \beta\Big(p_d A - C(\bar{x} - x) - rk\Big) \text{ and} \\ w_c &= (1-\beta) r J^U + \beta(p_c A - rk). \end{aligned} \tag{12}$$

A worker is compensated with fractions of his outside option value and the flow profit in the corresponding sector. Using equations (4), (7), (8), and (9), we have

$$rJ^U = z + \theta\frac{\beta}{1-\beta} rk. \tag{13}$$

rJ^U strictly increases with both θ and k. Intuitively, higher market tightness shortens unemployment spell, increasing a worker's outside option value.

Equations (7), (8), (12), and (13) imply the following zero-profit conditions:

$$rk = \frac{q(\theta)(1-\beta)}{r+\lambda}\left(p_d(\phi)A - C(\bar{x}-x) - rk - z - \frac{\theta\beta rk}{1-\beta}\right) \text{ and} \tag{14}$$

$$rk = \frac{q(\theta)(1-\beta)}{r+\lambda}\left(p_c(\phi)A - rk - z - \frac{\theta\beta rk}{1-\beta}\right). \tag{15}$$

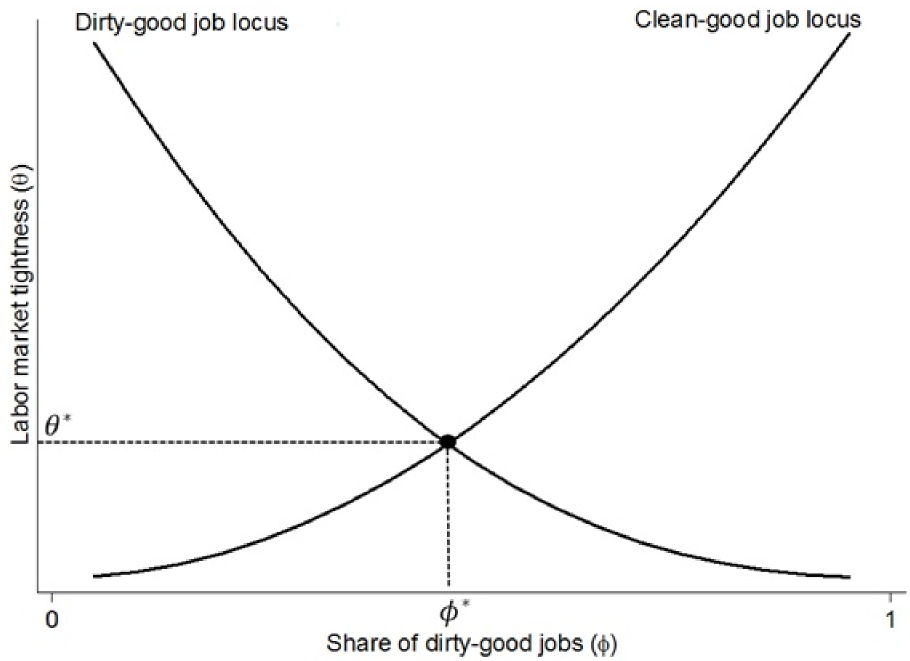

Figure 1: Equilibrium determination in the ϕ-θ plane

Along each locus, vacancies in the corresponding sector make zero expected profits. Using the two zero-profits conditions (14) and (15), the revenue differential between the two jobs is

$$\Lambda(\phi) \equiv p_d(\phi)A - p_c(\phi)A = 0, \tag{16}$$

which implies that $p_d = p_c$ in the equilibrium. Also, one can show that $\Lambda'(\phi) < 0$.

Proposition 1. *There exists a unique steady-state equilibrium, as defined in Definition 1.*

Proof. See Appendix 7.1. □

Figure 1 provides a graphical presentation of Proposition 1. It illustrates the determination of the equilibrium. In the $\phi - \theta$ plane, locus (14) slopes downward, and locus (15) slopes upward. An increase in the share of dirty-good jobs reduces the relative price of dirty goods, lowering the expected profits of its vacancies. Consequently, the supply of the dirty-good vacancies and thus market tightness decline. A similar intuition can be derived from the positive slope of the locus (15). The two loci intersect only once in the domain $\phi \in (0, 1)$, and the equilibrium is the intersection of the two loci.

3 Environmental Policy Selection Criteria

This section presents two policy selection criteria regarding employment and environmental quality. We demonstrate the applications of these criteria using the model framework presented in Section 2 to illustrate a policy dilemma: the tradeoff between employment and environmental quality. These criteria are important because the policy dilemma constrains the political feasibility of environmental policymaking and is the focus of many researches on policy designs.

3.1 Definitions

In the steady-state equilibrium, there are $\phi(1-u)$ number of jobs producing the dirty good, and each job emits x units of pollutant. Denote the *aggregate* emission level (i.e., the steady-state level of emission stock) by χ, which is

$$\chi \equiv x\phi(1-u). \tag{17}$$

There are three margins of change in the aggregate emission level, as the following equation shows:

$$d\chi = \underbrace{\phi(1-u)dx}_{\text{Intensive Margin}} + \underbrace{x(1-u)d\phi}_{\text{Extensive Margin}} + \underbrace{x\phi d(1-u)}_{\text{Scale Effect}}. \tag{18}$$

Changes in x and ϕ are adjustments in the intensive and the extensive margins of emission, respectively. A change in $1-u$ represents the scale effect on emission: holding emission per job and the composition of jobs constant, more output leads to more emission stock in a steady-state equilibrium. From a ruling party or a policymaker's perspective, more employment and output are preferred. This preference could create a scale effect that deteriorates the environmental quality. To normalize the output scale so that we can focus on the intensive and extensive margins of emission, we use an emission per unit of output (i.e., relative emission level) as a measure of environmental quality, which is

$$\varphi \equiv \frac{\chi}{Y}.$$

Using the above definition, equations (1) and (17) imply that

$$\varphi = \frac{x\phi(1-u)}{\left(\alpha Y_d^\rho + (1-\alpha)Y_c^\rho\right)^{\frac{1}{\rho}}} = \frac{x\phi}{A\left(\alpha\phi^\rho + (1-\alpha)(1-\phi)^\rho\right)^{\frac{1}{\rho}}}, \tag{19}$$

which shows that φ strictly increases with x and ϕ.[7] That is, emission (relative to output)

[7]The policy instrument, intensity standard, shares a similar notion of this criteria. While intensity standards

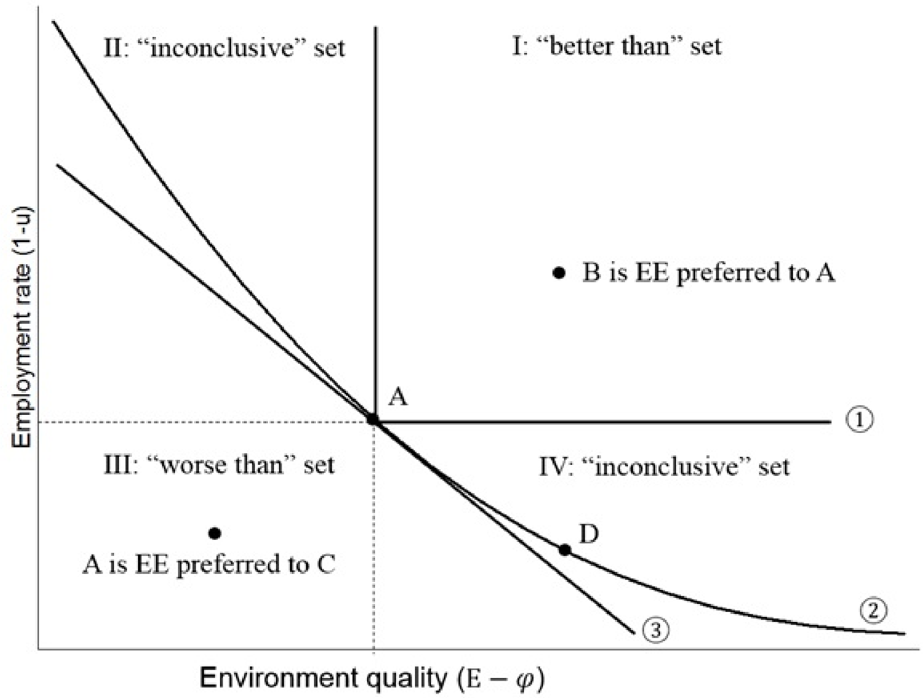

Figure 2: EE preference

increases, thus (normalized) environmental quality deteriorates, along both the intensive and extensive margins.

Next, we define a policymaker's policy preference over u and φ. We assume that the policymaker desires high levels of employment rate (low u) and environmental quality (low φ). Formally, we define the policy preference for employment rate and environmental quality (EE preference) as follows.

Definition 2. *A policy is a set of economic parameters and constraints that determine the steady-state equilibrium objects in the model. Let $u^{\mathcal{P}}$ and $\varphi^{\mathcal{P}}$ denote steady-state equilibrium objects under policy $\mathcal{P}$. Policy $\mathcal{P}_1$ is said to be EE preferred to policy $\mathcal{P}_2$ iff $u^{\mathcal{P}_1} \leq u^{\mathcal{P}_2}$ and $\varphi^{\mathcal{P}_1} \leq \varphi^{\mathcal{P}_2}$, where the equality holds at most once.*

In other words, an EE preferable policy reduces unemployment while keeping a relative emission level unchanged, or reduce a relative emission level while keeping unemployment unchanged, or reduces both unemployment and a relative emission level, compared to another policy. Rational policymakers should always choose the EE preferable policy over other policies whenever possible.

Figure 2 illustrates the concept of the EE preference in the plane defined by employment rate $(1-u)$ and environmental quality $E-\varphi$, where E could be any constant number. For

limit emissions per unit of dirty-good output, the criteria φ uses emissions per unit of final-good output to compare environmental quality among environmental policies.

any policy-generated equilibrium A, the collection of equilibria such that $1-u > 1-u^A$ and $E-\varphi > E-\varphi^A$ defines the set that is "better than" A (quadrant I). Notice that equilibria along the line (1) except the equilibrium A belong to this set. Any equilibrium in this set is EE preferred to A. Policies that generate the equilibria in this set are (likely) politically feasible because these policies gain support from local environmental organizations and labor unions/business circles.

We interpret the EE preferable policy as a "more" politically feasible policy throughout this paper. We realize that policy constraints in practice are not just created by local environmental organizations and labor unions/business circles. Our interpretation of the equivalence of the EE preference and the political feasibility is based on the assumption/approximation that the balance between the interests of these two lobbying groups is the major challenge in environmental policymaking.

The collection of equilibria (except A) such that $1-u \leq 1-u^A$ and $E-\varphi \leq E-\varphi^A$ is worse than equilibrium A (quadrant III): A is EE preferred to any equilibrium in this set. Everywhere else, the comparison between A and the other equilibria is inconclusive. For example, neither A nor D ($u^D > u^A$, $\varphi^D < \varphi^A$) is EE preferred to the other. While equilibria in quadrant II lose support from local environmental organizations, equilibria in quadrant IV do not favor labor unions or business circles.

Often, socially optimal policies maximize a specified social welfare function without considering the political feasibility. For example, if a social welfare function is represented by indifference curve 2, then D is as good as A; however, with indifference curve 3 (employment rate and environmental quality are perfect substitutes), D is better than A. In both cases, A is more politically feasible than D. The EE preference can be viewed as another class of social welfare functions that guarantee the political feasibility.

If two policies are not EE preferred to each other, it is inconclusive as to which policy should be chosen. The conclusion will depend on additional assumptions on the policymaker's policy preference (e.g., the marginal rate of substitution) and constraints. In this paper, we are interested in deriving the general results in our class of models. The advantage of the "EE preference" ranking is that we can abstract from specific details of the preference (such as the curvature of the indifference curves) so that our defined criterion are objective and measurable: they do not require researchers and policymakers to assign weights to each individual, and both the unemployment rate and the environmental quality are more easily observed and measured than the deep parameters in any utility function.

The disadvantage is that there is a large "inconclusive" set: the set of equilibria that cannot be ranked. To rank equilibria in this "inconclusive" set, we need to make specific assumptions. In the following sections, we will first settle for establishing whether the equilibrium of one policy is in the "better than" set of the other (Section 4), then discuss whether an equilibrium in the inconclusive set is better than A under more details of the preference (i.e., welfare implications using a more specific welfare function) (Section 5).

Analogously, we can define the concept of the *absolute* EE preference as follows.

Definition 3. *Policy $\mathcal{P}_1$ is said to be absolutely EE preferred to policy $\mathcal{P}_2$ iff $u^{\mathcal{P}_1} \leq u^{\mathcal{P}_2}$ and $\chi^{\mathcal{P}_1} \leq \chi^{\mathcal{P}_2}$, where the equality holds at most once.*

In other words, a policy is absolutely EE preferable if it results in a lower unemployment rate and the same aggregate emission level, or a lower aggregate emission level and the same unemployment rate, or both a lower unemployment rate and a lower aggregate emission level, compared to another policy. In the rest of the paper, we will focus on discussing if a policy is EE preferred to another policy and will only discuss the ranking under the absolute EE preference as a by-product if it requires insignificant marginal effort.

Lastly, we define a benchmark with which to compare policies. The benchmark is a state of no government intervention on pollutant emission. We call it the null policy ("policymakers doing nothing") and formally define it as follows.

Definition 4. *Under the null policy $\varnothing$, the equilibrium is defined in Definition 1.*

We can think the null policy as a "business as usual" case. The government does not punish polluting firms. Under the null policy, firms have no incentive to abate emission and will emit the maximum amount $\bar{x}$. The economy is in the "laissez-faire" equilibrium if policymakers choose the null policy. We implicitly consider $\varnothing$ as one of the policy choices. The comparison between $\varnothing$ and other environmental policies does suggest whether an economy should introduce a new environmental policy. And the comparison among other environmental policies provides information on which environmental policies are more politically feasible.

3.2 Environmental Impossibility Theorems

This subsection illustrates four theorems and their intuitions behind the tradeoff between the employment rate and the environmental quality. These theorems can be widely used to analyze the political feasibility between any two policies. We will show the applications of these theorems in several commonly seen environmental policies in Section 4.

Because unemployment strictly decreases with θ according to equation (10), u tends to zero when θ approaches positive infinity and to one when θ approaches zero, we can map the equilibrium conditions (14) and (15) from the ϕ-θ plane to the ϕ-u plane as shown in Figure 3. Clearly, if locus (14) shifts up along locus (15) while locus (15) is fixed, unemployment u will go up while ϕ goes down; that is, a tradeoff between employment and environmental quality along its extensive margin is inevitable. We will formalize this intuition below in Theorems 1-4.

In what follows, we formulate a general situation in which there is an additional flow cost T imposed on dirty-good production by the government. Accordingly, we rewrite the

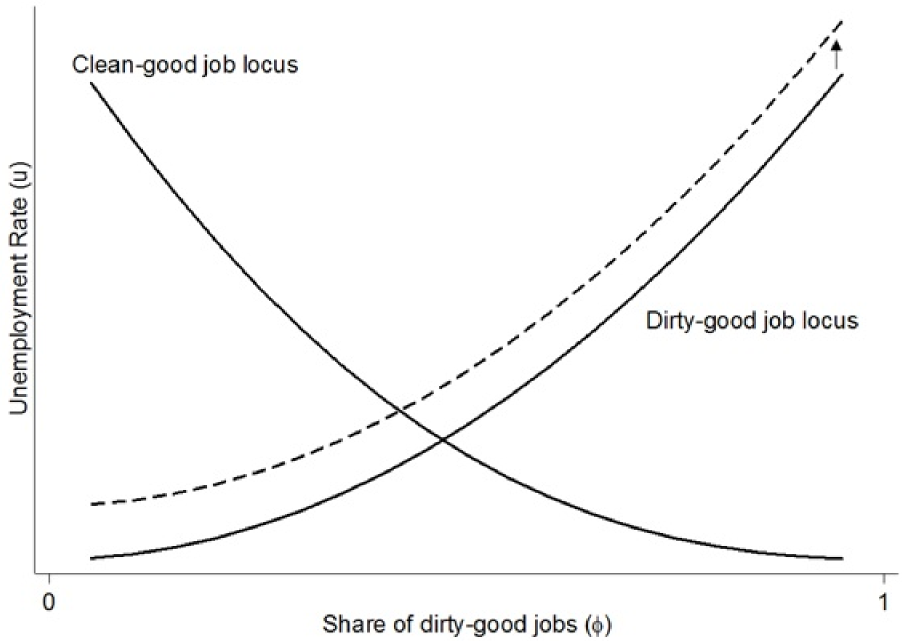

Figure 3: Equilibrium determination in the ϕ-u plane

zero-profit condition of a dirty-good job as

$$rk \;\; = \;\; \frac{q(\theta)(1-\beta)}{r+\lambda}\left(p_d(\phi)A - T - rk - z - \frac{\theta\beta rk}{1-\beta}\right). \tag{20}$$

The zero-profit condition of a clean-good job remains unchanged and is given by equation (15). The characteristic of this type of policy is that it only affects the flow cost of dirty-good production. It is straightforward to see in Figure 3 that the larger the cost T, the more the locus (20) shifts upward. Consequently, the unemployment rate will increase more, and the share of dirty-good jobs will decrease more. Such impacts can also be seen from the revenue differentials between the two jobs:

$$\Lambda(\phi) = T. \tag{21}$$

A higher T implies a lower ϕ in a steady-state equilibrium because $\Lambda'(\phi) < 0$. Intuitively, a higher flow cost makes the production of dirty goods costlier, reducing the supply of its vacancies θ and its market share ϕ. Since clean goods become more abundant, its price goes down, depressing the supply of its vacancies. This general equilibrium effect further decreases market tightness θ, and thus increases u. The following theorem indicates that policies of this class will have opposite effects on the unemployment rate and the job composition relative to each other. In other words, the tradeoff between employment and environmental quality along its extensive margin is inevitable among policies of this class.

Theorem 1. *Denote Υ as a class of policies that imposes the flow cost $T \geq 0$ on dirty-good* *jobs. For all policies $\mathcal{P}_1, \mathcal{P}_2 \in \Upsilon$, if $T_1 = T_2$, then $u^{\mathcal{P}_1} = u^{\mathcal{P}_2}$ and $\phi^{\mathcal{P}_1} = \phi^{\mathcal{P}_2}$, and if $T_1 > T_2$, then $u^{\mathcal{P}_1} > u^{\mathcal{P}_2}$ and $\phi^{\mathcal{P}_1} < \phi^{\mathcal{P}_2}$.*

It is noteworthy that Theorem 1 holds as long as the policy increases the flow cost in dirty-good jobs, not clean-good jobs. Despite there being no direct flow cost in clean-good jobs, this theorem does allow the general equilibrium effect of the flow cost in dirty-good jobs on clean-good jobs. Another important highlight is that this theorem does not restrict the impacts of the policy of this class on emission along its intensive margin or predict anything about the intensive margin of emission. Next, Theorem 2 translates the tradeoff in Theorem 1 into the (absolute) EE preference ranking of environmental policies.

Theorem 2. *Denote $\Psi(x)$ as a class of policies such that (i) $\Psi(x) \subseteq \Upsilon$, and (ii) the equilibrium emission level per job under policies $\mathcal{P} \in \Psi(x)$ equals $x \in [0, \bar{x}]$. For all policies $\mathcal{P}_1, \mathcal{P}_2 \in \Psi(x)$, $\mathcal{P}_1$ is not (absolutely) EE preferred to $\mathcal{P}_2$.*

Proof. Suppose $\mathcal{P}_1$ and $\mathcal{P}_2$ belong to $\Psi(x)$. Without loss of generality, we assume $T_1 \geq T_2$. If $T_1 = T_2$, then $u^{\mathcal{P}_1} = u^{\mathcal{P}_2}$ and $\phi^{\mathcal{P}_1} = \phi^{\mathcal{P}_2}$. Since $\mathcal{P}_1$, $\mathcal{P}_2 \in \Psi(x)$, $x^{\mathcal{P}_1} = x^{\mathcal{P}_2} = x$. Hence, $\varphi^{\mathcal{P}_1} = \varphi^{\mathcal{P}_2}$ and $\chi^{\mathcal{P}_1} = \chi^{\mathcal{P}_2}$. These two policies are not (absolutely) EE preferred to each other. If $T_1 > T_2$, then $u^{\mathcal{P}_1} > u^{\mathcal{P}_2}$ and $\phi^{\mathcal{P}_1} < \phi^{\mathcal{P}_2}$. Hence, $u^{\mathcal{P}_1} > u^{\mathcal{P}_2}$, $\varphi^{\mathcal{P}_1} < \varphi^{\mathcal{P}_2}$, and $\chi^{\mathcal{P}_1} < \chi^{\mathcal{P}_2}$. These two policies are not (absolutely) EE preferred to each other. □

In particular, there may exist policies that share the same emission level along the intensive margin like the null policy. A direct application of Theorem 2 to policies of this class implies the following theorem.

Theorem 3. *There exists no $\mathcal{P} \in \Psi(\bar{x})$ such that $\mathcal{P}$ is (absolutely) EE preferred to $\varnothing$.*

Theorem 2 and Theorem 3 prove an important (even crucial) theory in understanding the economic impacts of environmental regulation policies: regulation is costly. In the simplest case where the regulation only affects the economic parameters of the polluting sector, it is clear why regulating dirty-good production will cost jobs relative to doing nothing. The reason is that the increase in the flow cost of dirty-good vacancies depreciates their value. Firms will then open less dirty-good vacancies relative to clean-good vacancies. The change in job composition translates into changes in relative prices and in turn affects the profit conditions of both types of job. The value of clean-good vacancies will also be negatively affected because of the downward general equilibrium effect on clean-good price. The outcome is that the number of vacancies will decrease and the market will become tighter. Consequently, unemployment rises.

Indeed, these policy instruments belong to a broad class of policies—policies that increase the flow cost of the polluting sector by $T \geq 0$ with emission no more than x. We denote this class of policies by $\Omega(x, T)$. Under any policy in $\Omega(x, T)$, the zero-profit conditions of a clean-good job and a dirty-good job are given by (15) and (20), respectively.

Notice that Theorem 3 is a direct application of Theorem 2 to the cases in which emission on the firm level is identical to $\bar{x}$, the emission under the null policy. This theorem indeed holds for any policy with emission no more than $\bar{x}$. Formally, there exists no $\mathcal{P} \in \Omega(\bar{x}, T)$ such that $\mathcal{P}$ is (absolutely) EE preferred to $\varnothing$. If $T = 0$, Theorem 1 concludes that $\mathcal{P}$ and $\varnothing$ are not (absolutely) EE preferred to each other because $\mathcal{P}$ and $\varnothing$ are equivalent when $T = 0$. If $T > 0$, Theorem 1 implies that $u^{\mathcal{P}} > u^{\varnothing}$. Therefore, no $\mathcal{P} \in \Omega(\bar{x}, T)$ is (absolutely) EE preferred to $\varnothing$.

This theorem also holds in a reverse direction. In other words, $\varnothing$ is not EE preferred any policy $\mathcal{P} \in \Omega(\bar{x}, T)$. Because of $T > 0$, Theorem 1 also implies that $\phi^{\mathcal{P}} < \phi^{\varnothing}$. Since $x^{\mathcal{P}} \leq \bar{x} = x^{\varnothing}$ by the definition of $\Omega(\bar{x}, T)$, $\varphi^{\mathcal{P}} < \varphi^{\varnothing}$ and thus $\chi^{\mathcal{P}} < \chi^{\varnothing}$. Now, we can conclude that $\mathcal{P}$ and $\varnothing$ are not (absolutely) EE preferred to each other for all $\mathcal{P} \in \Omega(\bar{x}, T)$.

This theorem can be easily generalized by comparing any two subclasses of policies with different combinations of x and T. The following theorem summarizes the result:

Theorem 4. *$\mathcal{P}_1$ and $\mathcal{P}_2$ are not (absolutely) EE preferred to each other for all $\mathcal{P}_j \in \Omega(x_j, T_j)$ if $x_1 \leq x_2$ and $T_1 \geq T_2$.*

Notice that $\varnothing \in \Omega(\bar{x}, 0)$. Hence, any environmental policies that increase the flow cost in a polluting sector without increasing its intensive margin of emission are not EE preferred to the null policy, and vice versa.

Theorem 4 outlines the reasons behind the non-stop lobbying in environmental policymaking. Local environmental organizations lobby against a laissez-faire equilibrium because there exists a broad class of policies that could improve environmental quality. Polluting industries and labor unions lobby against a broad class of environmental policies because of the unemployment effect. Lobbying continues because neither is more politically feasible than the other. Our result therefore lays the theoretical foundation of the conflicts between the two lobbying groups in the literature on the political economy of environmental policy (Aidt, 1998; Fredriksson and Svensson, 2003; Oates and Portney, 2003; List and Sturm, 2006). Moreover, our finding rules out this broad class of policy if the political feasibility is a concern.

Policies that affect other parameters of the model will open additional adjustment margins that would change the economic outcomes in the equilibrium. Thus, it is possible to manipulate parameters in a sophisticated way such that both unemployment drops and environmental quality improves relative to business as usual or other environmental policies. We formally discuss this possibility in the next section.

4 Environmental Policies

This section examines the EE preferability among several commonly seen policies: a lump-sum tax on dirty-good jobs (Section 4.1), a per-unit emission tax (Section 4.2), and an intensity standard (Section 4.3). The examination of these policies is informative for three reasons.

First, it provides information whether these policies are politically feasible over the null policy. It provides support for/against the introduction of these environmental policies to an economy. Second, it provides guidance in policy choices. When policymakers consider among these polices, our analysis provides information on which one is more politically feasible (Section 4.4). Third, our general framework applies to a wide range of environmental policies. This section demonstrates the applications of the *Environmental Impossibility Theorems* in understanding the political feasibility of commonly seen policies, which serves as the showcase for future applications in examining other environmental policies.

4.1 Lump-Sum Tax on Dirty-Good Production

Suppose a lump-sum tax $T > 0$ is levied on each dirty-good job. Meanwhile, this policy has no impact on the abatement cost or abatement benefit, leaving the optimal abatement level zero. While the emission per dirty-good job remains unchanged, the emission level per dirty-goods job, equal to $\bar{x}$, is identical under this policy and $\varnothing$, the direct application of Theorem 3 implies that this lump-sum tax policy and the null policy are not (absolutely) EE preferred to each other.

Figure 3 demonstrates the graphical representation of a positive lump-sum tax T. Under this policy, the zero-profit condition of a dirty-good job is given by equation (20) while the zero-profit condition of a clean-good job (given by equation (15)) remains intact. The unemployment rate rises and the share of the dirty-good job declines, as predicted by Theorem 1. We omit the intuition here because Section 3.2 discusses a similar intuition in details. Hence, the following proposition summarizes the findings.

Proposition 2. *For all $T \geq 0$, the lump-sum tax on dirty-good production and $\varnothing$ are not (absolutely) EE preferred to each other.*

4.2 Per-Unit Emission Tax

This subsection explores the political feasibility of a per-unit emission tax policy and the mechanisms through this policy affects the labor market and the environmental quality. Suppose the tax paid by a dirty-good producer who emits x units of pollutant is τx.[8] Firms

[8]We can extend the model to allow nonlinear tax schemes by replacing τx in equation (22) by $T(x)$, which denotes the total tax on emission level x, and τ in equation (23) by $T'(x)$, which is the first derivative of $T(x)$. We will have to make appropriate assumptions on the differentiability and convexity of the function $T(x)$ to ensure the existence and uniqueness of the steady-state equilibrium. Such an extension does not yield additional economic intuition. Thus, in this paper, we stick with the simple case of the linear tax scheme.

that produce dirty goods choose the emission level x to maximize the asset value of a filled job. Thus, the asset value of each job is given by:

$$\begin{aligned} rJ_d^F &= \max_{x\in[0,\bar{x}]} p_d A - w_d - C(\bar{x}-x) - \tau x + \lambda(J_d^V - J_d^F) \text{ and} \\ rJ_c^F &= p_c A - w_c + \lambda(J_c^V - J_c^F). \end{aligned} \tag{22}$$

The optimal emission level for each dirty-good job is the solution to the following first-order condition:

$$\underbrace{C'(\bar{x}-x)}_{\text{Marginal Abatement Cost}} = \underbrace{\tau}_{\text{Marginal Abatement Benefit}}. \tag{23}$$

Intuitively, an additional unit of abatement increases abatement cost by the marginal abatement cost but saves emission tax payment of this additional unit. In other words, the optimal emission level equates the marginal abatement cost to its marginal abatement benefit. Under the assumptions $\lim_{x\to\bar{x}} C'(\bar{x}-x) = 0$ and $\lim_{x\to 0} C'(\bar{x}-x) = \infty$, the intermediate value theorem ensures the existence of $x \in (0,\bar{x})$ that solves equation (23). Since $C''(\bar{x}-x) > 0$, the optimal emission level x is unique.

Accordingly, we rewrite the wage equation (12) as follows:

$$\begin{aligned} w_d &= (1-\beta)rJ^U + \beta(p_d A - C(\bar{x}-x) - \tau x - rk) \text{ and} \\ w_c &= (1-\beta)rJ^U + \beta(p_c A - rk). \end{aligned}$$

Similarly, the zero-profit condition for the dirty-good job (14) can be rewritten as follows:

$$rk = \frac{q(\theta)(1-\beta)}{r+\lambda}\left(p_d A - C(\bar{x}-x) - \tau x - rk - z - \frac{\theta\beta rk}{1-\beta}\right). \tag{24}$$

And the revenue differential (21) is now given by

$$\Lambda(\phi) = C(\bar{x}-x) + \tau x. \tag{25}$$

The unique equilibrium exists by arguments similar to that in Appendix 7.1. We denote this emission tax policy by $\mathcal{ET}(\tau)$, where $\tau \in \mathbb{R}_+$.

Totally differentiating the revenue differential (25) with respect to τ, we have $d\phi/d\tau = x[\Lambda'(\phi)]^{-1} < 0$. Using the zero-profit condition for the clean-good job (15), $du/d\tau > 0$ follows through changes in labor market tightness θ. Intuitively, an increase in the emission tax incents abatement, reducing the emission level x from the intensive margin. Hence, the tax incurs both the emission tax payment and the abatement cost, reducing the expected profits for dirty-good vacancies and thus depressing their supply. The reduction in the supply of these vacancies expands the share of the clean-good vacancies; this general equilibrium effect reduces the price of clean goods. Consequently, the expected profits and thus the supply of the vacancies decline in the nonpolluting sector. Since the supplies of the vacancies of both types decline, labor market tightness decreases, and the unemployment rate increases.

The change in aggregate emission in response to changes the emission tax can be seen by

$$\frac{d\chi}{d\tau} = \underbrace{\phi(1-u)\frac{dx}{d\tau}}_{<0} + \underbrace{x(1-u)\frac{d\phi}{d\tau}}_{<0} + \underbrace{x\phi\frac{d(1-u)}{d\tau}}_{<0}.$$

The first term represents the reduction of emission on the intensive margin. A larger emission tax rate increases the cost of emission, giving firms incentives to abate emission. The second term represents the reduction of emission on the extensive margin. Emission tax payment and abatement cost increase the flow cost for dirty-good jobs, reduce their flow profits, and thus lower the supply of dirty-good vacancies. The third term represents the scale effect, which is through the general equilibrium effect on the clean-good price.

Finally, because $dx/d\tau < 0$ and $d\phi/d\tau < 0$, $d\varphi/d\tau < 0$. We summarize these results in Lemma 1.

Lemma 1. *For all* $\tau \in \mathbb{R}_+$, $\frac{dx}{d\tau} < 0$, $\frac{d\phi}{d\tau} < 0$, $\frac{d\varphi}{d\tau} < 0$, $\frac{d\chi}{d\tau} < 0$, *and* $\frac{du}{d\tau} > 0$.

From Lemma 1, Proposition 3 follows.

Proposition 3. ***(Emission Tax)*** *For all* $\tau \in \mathbb{R}_{++}$, $\mathcal{ET}(\tau)$ *and* $\varnothing$ *are not (absolutely) EE preferred to each other.*

Proof. $\tau = 0$ corresponds to $\varnothing$. $u^{\mathcal{ET}}(\tau) = u^{\varnothing}$ when $\tau = 0$. Lemma 1 implies $u^{\mathcal{ET}}(\tau) > u^{\varnothing}$, $\varphi^{\mathcal{ET}}(\tau) < \varphi^{\varnothing}$, and $\chi^{\mathcal{ET}}(\tau) < \chi^{\varnothing}$ for all $\tau \in \mathbb{R}_{++}$. This completes the proof. □

These results can also be shown graphically as in Figure 3. Under $\mathcal{ET}(\tau)$, the flow cost $T^{\mathcal{ET}}(\tau)$ is equal to $C(\bar{x} - x) + \tau x > 0$, where x is the optimal emission level that solves equation (23). Theorem 1 is invoked: unemployment increases because of the positive $T^{\mathcal{ET}}(\tau)$. Hence, there exists no $\tau > 0$ such that $\mathcal{ET}(\tau)$ is EE preferred to $\varnothing$. Notice that $x^{\mathcal{ET}}(\tau) < \bar{x}$ and Environmental Impossibility Theorem 1 implies that $\phi^{\mathcal{ET}}(\tau) < \phi^{\varnothing}$ for all $\tau > 0$; therefore, $\varphi^{\mathcal{ET}}(\tau) < \varphi^{\varnothing}$ and $\chi^{\mathcal{ET}}(\tau) < \chi^{\varnothing}$, $\varnothing$ is not (absolutely) EE preferred to $\mathcal{ET}(\tau)$.

4.3 Intensity Standard

Next, we examine the political feasibility of intensity standard that caps the level of emission per A unit of dirty good at $\hat{x} \in (0, \bar{x})$. We denote this policy by $\mathcal{IS}(\hat{x})$, where $\hat{x} \in (0, \bar{x})$. Firms are not allowed to emit more than $\hat{x}$, and thus the optimal emission level is less than or equal to $\hat{x}$. In the absence of abatement benefit, a dirty-good job will not abate less than $\hat{x}$ because abatement is costly. Hence, the optimal emission level is given by $\hat{x}$. In other words, this job will match its emission level to $\hat{x}$. That is, $dx^{\mathcal{IS}}(\hat{x})/d\hat{x} > 0$.

The flow cost in each dirty-good job $T^{\mathcal{IS}}(\hat{x})$ is equal to $C(\bar{x}-\hat{x}) > 0$ under $\mathcal{IS}(\hat{x})$. The more restrictive the intensity standard, the higher the optimal emission level and the higher the flow cost. Environmental Impossibility Theorem 1 concludes that $d\phi^{\mathcal{IS}}(\hat{x})/d\hat{x} > 0$ and $du^{\mathcal{IS}}(\hat{x})/d\hat{x} > 0$. It is also expected from Figure 3 that the unemployment rate will increase and the share of the polluting sector will shrink under policy $\mathcal{IS}(\hat{x})$ because of the positive $T^{\mathcal{IS}}(\hat{x})$. $dx^{\mathcal{IS}}(\hat{x})/d\hat{x} > 0$, $d\phi^{\mathcal{IS}}(\hat{x})/d\hat{x} > 0$, and $du^{\mathcal{IS}}(\hat{x})/d\hat{x} > 0$ imply $d\varphi^{\mathcal{IS}}(\hat{x})/d\hat{x} > 0$ and $d\chi^{\mathcal{IS}}(\hat{x})/d\hat{x} > 0$. We omit the intuition here because it is similar to the impact of $\mathcal{ET}(\tau)$ on the labor market and the environmental quality. We summarize these results in Lemma 2.

Lemma 2. *For all $\hat{x} \in (0, \bar{x})$, $\frac{dx}{d\hat{x}} > 0$, $\frac{d\phi}{d\hat{x}} > 0$, $\frac{d\varphi}{d\hat{x}} > 0$, $\frac{d\chi}{d\hat{x}} > 0$ and $\frac{du}{d\hat{x}} < 0$.*

From Lemma 2, Proposition 4 follows.

Proposition 4. ***(Intensity Standard)*** *For all $\hat{x} \in (0, \bar{x})$, $\mathcal{IS}(\hat{x})$ and $\varnothing$ are not (absolutely) EE preferred to each other.*

Up to this point, this section demonstrated the applications of the *Environmental Impossibility Theorems* to show that the three commonly seen policies and the null policy are not EE preferred to each other. Indeed, these policy instruments belong to $\Omega(x, T)$ in Section 3.2. For example, the null policy belongs to $\Omega(x, 0)$ for all $x \geq \bar{x}$, and a lump-sum tax policy belongs to $\Omega(x, T)$ for all $x \geq \bar{x}$. A per-unit emission tax policy $\mathcal{ET}(\tau)$ belongs to $\Omega(x, T^{\mathcal{ET}}(\tau))$ for all $x \geq x^{\mathcal{ET}}(\tau)$, where $T^{\mathcal{ET}}(\tau) = C(\bar{x} - x) + \tau x$ and x solves the first-order condition (23).[9] Similarly, $\mathcal{IS}(\hat{x}) \in \Omega(x, T^{\mathcal{IS}}(\hat{x}))$ for all $\hat{x} \in [0, \bar{x}]$ and $x \geq \hat{x}$, where $T^{\mathcal{IS}}(\hat{x}) = C(\bar{x} - \hat{x})$. Therefore, all these policy instruments are subject to Theorem 4, and Theorem 4 implies Propositions (2)-(4).

Note that the *Environmental Impossibility Theorems* are built on conditions regarding the flow cost on dirty-good jobs and the intensive margin of emission. The next analysis explores what happens outside the theorem conditions. To wit, we seek to design policies that are EE preferred to other policies in the same class or in the other classes.

4.4 Comparisons Between Emission Tax and Intensity Standard

This subsection answers the question: between emission tax and intensity standard, is it possible to design one that is EE preferred to the other? The answer to this question is interesting to policymakers who are constrained to choose between these policies. Suppose there is a prevalent emission tax of rate τ in the economy, and the policymaker considers

[9] Since $x^{\mathcal{ET}}(\tau) < \bar{x}$, $\mathcal{ET}(\tau) \in \Omega(x, T^{\mathcal{ET}}(\tau))$ for all $x \geq \bar{x}$.

replacing the tax by intensity standard. This section answers whether there exist intensity standards $\hat{x}$ such that this policy shift simultaneously reduces unemployment and improves environmental quality. Similarly, it explores whether there exist emission taxes τ such that the policy shift from emission tax to intensity standard reduces unemployment and improves environmental quality.

First, we assume the economy begins with a prevalent emission tax with rate $\tau > 0$. As discussed in Sections 4.2 and 4.3, $T^{\mathcal{ET}}(\tau) = C(\bar{x} - x^{\mathcal{ET}}(\tau)) + \tau x^{\mathcal{ET}}(\tau)$ and $T^{\mathcal{IS}}(\hat{x}) = C(\bar{x} - \hat{x})$. Given τ, there exists a unique $x_\phi(\tau) \in (0, \bar{x})$ such that $T^{\mathcal{IS}}(x_\phi(\tau)) = T^{\mathcal{ET}}(\tau)$ because $\lim_{x \to \bar{x}} C'(\bar{x} - x) = 0$, $\lim_{x \to 0} C'(\bar{x} - x) = \infty$, and $C'(\bar{x} - x) > 0$. Since $dT^{\mathcal{ET}}(\tau)/d\tau > 0$ and $dT^{\mathcal{IS}}(\hat{x})/d\hat{x} < 0$, $dx_\phi(\tau)/d\tau < 0$.

Since the flow costs are identical, Environmental Impossibility Theorem 1 implies that $u^{\mathcal{IS}}(x_\phi(\tau)) = u^{\mathcal{ET}}(\tau)$ and $\phi^{\mathcal{IS}}(x_\phi(\tau)) = \phi^{\mathcal{ET}}(\tau)$. This is the equilibrium A in Figure 4. Intuitively, the revenue differentials are identical under policies $\mathcal{ET}(\tau)$ and $\mathcal{IS}(x_\phi(\tau))$. That is, $\Lambda(\phi^{\mathcal{IS}}(x_\phi(\tau))) = T^{\mathcal{IS}}(x_\phi(\tau)) = T^{\mathcal{ET}}(\tau) = \Lambda(\phi^{\mathcal{ET}}(\tau))$. Hence, $\phi^{\mathcal{IS}}(x_\phi(\tau)) = \phi^{\mathcal{ET}}(\tau)$.

While the entire flow cost is used for abatement under the intensity standard, a portion of the flow cost is the emission tax payment under the emission tax. Since $T^{\mathcal{IS}}(x_\phi(\tau)) = T^{\mathcal{ET}}(\tau)$, more resources are used to abate emission under the intensity standard. Hence, $x^{\mathcal{IS}}(x_\phi(\tau)) < x^{\mathcal{ET}}(\tau)$. Now, it is straightforward to see that $\varphi^{\mathcal{IS}}(x_\phi(\tau)) < \varphi^{\mathcal{ET}}(\tau)$ and $\chi^{\mathcal{IS}}(x_\phi(\tau)) < \chi^{\mathcal{ET}}(\tau)$. $\mathcal{IS}(x_\phi(\tau))$ is (absolutely) EE preferred to $\mathcal{ET}(\tau)$ because of the better environmental quality.

There exists no intensity standard $\hat{x} \in [0, x_\phi(\tau)]$ such that $\mathcal{IS}(\hat{x})$ is (absolutely) EE preferred to $\mathcal{ET}(\tau)$. Since a more stringent intensity standard than $x_\phi(\tau)$ further increases the abatement cost and thus the flow cost (i.e., $dT^{\mathcal{IS}}(\hat{x})/d\hat{x} < 0$), $T^{\mathcal{IS}}(\hat{x}) > T^{\mathcal{IS}}(x_\phi(\tau))$ for all $\hat{x} \in [0, x_\phi(\tau)]$. Again, Environmental Impossibility Theorem 1 is invoked: $u^{\mathcal{IS}}(\hat{x}) > u^{\mathcal{IS}}(x_\phi(\tau))$ for all $\hat{x} \in [0, x_\phi(\tau)]$. As $u^{\mathcal{IS}}(\hat{x}) > u^{\mathcal{IS}}(x_\phi(\tau)) = u^{\mathcal{ET}}(\tau)$, we can conclude that $\mathcal{IS}(\hat{x})$ is not (absolutely) EE preferred to $\mathcal{ET}(\tau)$ because of the higher unemployment rate for all $\hat{x} \in [0, x_\phi(\tau)]$. They are the equilibria to the left of the equilibrium A in Figure 4.

What about the equilibria to the right of the equilibrium A? Next, we compare between $\mathcal{ET}(\tau)$ and $\mathcal{IS}(x^{\mathcal{ET}}(\tau))$, where $\mathcal{IS}(x^{\mathcal{ET}}(\tau))$ caps the emission level at the optimal emission level under $\mathcal{ET}(\tau)$. Hence, the optimal emission levels and thus the abatement costs are identical under these two policies. Since the optimal emission levels are identical, Environmental Impossibility Theorem 2 is invoked: $\mathcal{IS}(x^{\mathcal{ET}}(\tau))$ and $\mathcal{ET}(\tau)$ are not (absolutely) EE preferred to each other. In addition to the abatement cost, dirty-job firms are required to pay an emission tax under $\mathcal{ET}(\tau)$. Therefore, $T^{\mathcal{IS}}(x^{\mathcal{ET}}(\tau)) < T^{\mathcal{ET}}(\tau)$. Since $T^{\mathcal{IS}}(x^{\mathcal{ET}}(\tau)) < T^{\mathcal{ET}}(\tau) = T^{\mathcal{IS}}(x_\phi(\tau))$, Environmental Impossibility Theorem 1 implies that $u^{\mathcal{IS}}(x^{\mathcal{ET}}(\tau)) < u^{\mathcal{IS}}(x_\phi(\tau))$ and $\phi^{\mathcal{IS}}(x^{\mathcal{ET}}(\tau)) > \phi^{\mathcal{IS}}(x_\phi(\tau))$, which is the equilibrium C in Figure 4. Since $x^{\mathcal{IS}}(x^{\mathcal{ET}}(\tau)) = x^{\mathcal{ET}}(\tau)$ and $\phi^{\mathcal{IS}}(x^{\mathcal{ET}}(\tau)) > \phi^{\mathcal{ET}}(\tau)$,

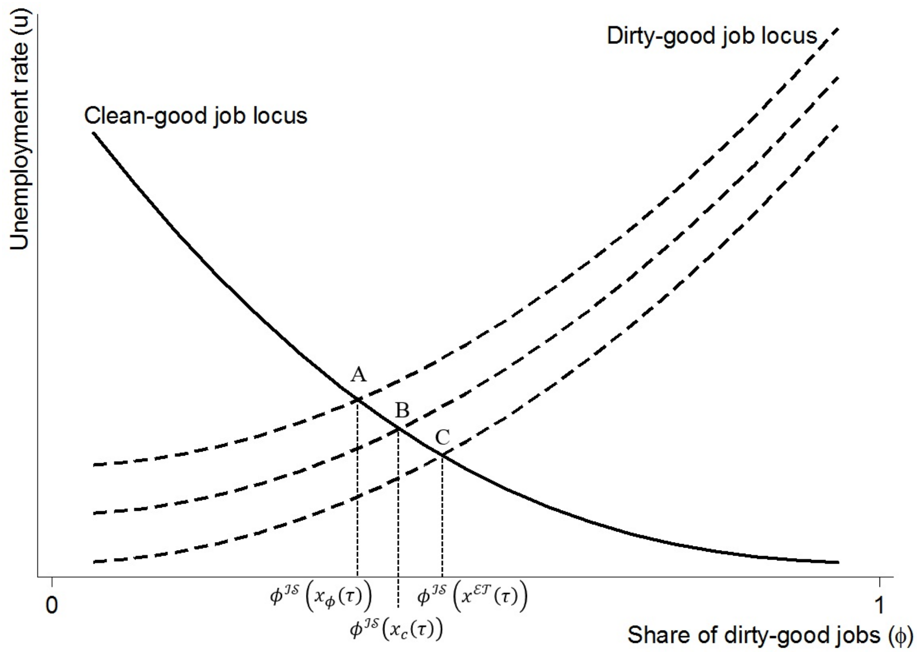

Figure 4: Comparisons between emission tax and intensity standard

the emission per output is lower under $\mathcal{IS}(x^{\mathcal{ET}}(\tau))$. That is, $\varphi^{\mathcal{IS}}(x^{\mathcal{ET}}(\tau)) > \varphi^{\mathcal{ET}}(\tau)$.

We have shown in the last two paragraphs that $\varphi^{\mathcal{IS}}(x_\phi(\tau)) < \varphi^{\mathcal{ET}}(\tau) < \varphi^{\mathcal{IS}}(x^{\mathcal{ET}}(\tau))$. Lemma 2 indicates that $d\varphi^{\mathcal{IS}}(x_\phi(\tau))/d\hat{x} > 0$. Hence, there must exist a unique $x_c(\tau) \in (x_\phi(\tau), x^{\mathcal{ET}}(\tau))$ such that $\varphi^{\mathcal{IS}}(\hat{x}) < \varphi^{\mathcal{ET}}(\tau)$ for all $\hat{x} \in (x_\phi(\tau), x_c(\tau))$ and $\varphi^{\mathcal{IS}}(x_c(\tau)) = \varphi^{\mathcal{ET}}(\tau)$, which is the equilibrium B in Figure 4. It is straightforward to see that the unemployment rate is lower under $\mathcal{IS}(\hat{x})$ than under $\mathcal{ET}(\tau)$ for all $\hat{x} \in (x_\phi(\tau), x_c(\tau))$.[10] Now, we can summarize our findings.

Proposition 5. *Given any emission tax $\tau \in \mathbb{R}_{++}$, there always exists a corresponding interval of intensity standard $\hat{x} \in [x_\phi(\tau), x_c(\tau)]$ such that $\mathcal{IS}(\hat{x})$ is EE preferred to $\mathcal{ET}(\tau)$, where $x_\phi(\tau)$ solves $C(\bar{x} - x_\phi(\tau)) = C(\bar{x} - x^{\mathcal{ET}}(\tau)) + \tau x^{\mathcal{ET}}(\tau)$ and $x_c(\tau) \in (x_\phi(\tau), x^{\mathcal{ET}}(\tau))$.*

In what follows, we answer whether there exists an emission tax rate such that the emission tax policy is EE preferred to intensity standard. Suppose an economy is prevalent with an intensity standard policy $\mathcal{IS}(\hat{x})$, where $\hat{x} \in (0, \bar{x})$. Section 4.3 indicates that $x^{\mathcal{IS}}(\hat{x}) = \hat{x}$ and the flow cost is equal to $T^{\mathcal{IS}}(\hat{x}) = C(\bar{x} - x^{\mathcal{IS}}(\hat{x}))$. Similar to the analysis above, there always exists an emission tax $\tau_\phi(\hat{x}) \in \mathbb{R}_{++}$ such that $T^{\mathcal{IS}}(\hat{x}) = T^{\mathcal{ET}}(\tau_\phi(\hat{x})) = C(\bar{x} - x^{\mathcal{ET}}(\tau_\phi(\hat{x}))) + \tau_\phi(\hat{x}) x^{\mathcal{ET}}(\tau_\phi(\hat{x}))$. Since $T^{\mathcal{IS}}(\hat{x}) = T^{\mathcal{ET}}(\tau_\phi(\hat{x}))$, Environmental Impossibility Theorem 1 implies that $u^{\mathcal{IS}}(\hat{x}) = u^{\mathcal{ET}}(\tau_\phi(\hat{x}))$ and $\phi^{\mathcal{IS}}(\hat{x}) = \phi^{\mathcal{ET}}(\tau_\phi(\hat{x}))$.

[10] It is easy to show that $u^{\mathcal{ET}}(\tau) = u^{\mathcal{IS}}(x_\phi(\tau)) > u^{\mathcal{IS}}(x_c(\tau))$.

While the entire flow cost is used for abatement under the intensity standard, a portion of the flow cost is the emission tax payment under the emission tax. Since $T^{\mathcal{IS}}(\hat{x}) = T^{\mathcal{ET}}(\tau_\phi(\hat{x}))$, more resources are used to abate emission under the intensity standard. Hence, $x^{\mathcal{IS}}(\hat{x}) < x^{\mathcal{ET}}(\tau_\phi(\hat{x}))$. Now, it is straightforward to see that $\varphi^{\mathcal{IS}}(\hat{x}) < \varphi^{\mathcal{ET}}(\tau_\phi(\hat{x}))$ and $\chi^{\mathcal{IS}}(\hat{x}) < \chi^{\mathcal{ET}}(\tau_\phi(\hat{x}))$. $\mathcal{ET}(\tau_\phi(\hat{x}))$ is not (absolutely) EE preferred to $\mathcal{IS}(\hat{x})$ because of the poorer environmental quality.

There exists no emission tax $\tau \in [0, \tau_\phi(\hat{x}))$ such that $\mathcal{ET}(\tau)$ is (absolutely) EE preferred to $\mathcal{IS}(\hat{x})$. By Lemma 1, a reduction in the emission tax rate increases emissions along both margins and thus the total emission per output, and the aggregate emission. Since $\varphi^{\mathcal{IS}}(\hat{x}) < \varphi^{\mathcal{ET}}(\tau_\phi(\hat{x}))$, $\varphi^{\mathcal{IS}}(\hat{x}) < \varphi^{\mathcal{ET}}(\tau)$ for all $\tau \in [0, \tau_\phi(\hat{x}))$. Hence, $\mathcal{ET}(\tau)$ is not EE preferred to $\mathcal{IS}(\hat{x})$ for all $\tau \in [0, \tau_\phi(\hat{x}))$ because of the higher total emission per output.

Next, we will show that there exists no emission tax $\tau > \tau_\phi(\hat{x})$ such that $\mathcal{ET}(\tau)$ is (absolutely) EE preferred to $\mathcal{IS}(\hat{x})$. Since $T^{\mathcal{ET}}(\tau_\phi(\hat{x})) = T^{\mathcal{IS}}(\hat{x})$, $T^{\mathcal{ET}}(\tau) > T^{\mathcal{IS}}(\hat{x})$ for all $\tau > \tau_\phi(\hat{x})$ because any increase in the emission tax will increase the flow cost as discussed in Section 4.2. Environmental Impossibility Theorem 1 is invoked: $u^{\mathcal{ET}}(\tau) > u^{\mathcal{IS}}(\hat{x})$ for all $\tau > \tau(\hat{x})$. Hence, no $\mathcal{ET}(\tau)$ is (absolutely) EE preferred to $\mathcal{IS}(\hat{x})$ for all $\tau > \tau_\phi(\hat{x})$ because of the higher unemployment rate. Proposition 6 summarizes our findings.

Proposition 6. *Given any intensity standard $\hat{x} \in (0, \bar{x})$, there exists no emission tax rate $\tau \in \mathbb{R}_{++}$ such that $\mathcal{ET}(\tau)$ is (absolutely) EE preferred to $\mathcal{IS}(\hat{x})$.*

This section concludes that an intensity standard is superior to an emission tax if (i) there is a political concern on the tradeoff between unemployment and emission, and (ii) the consideration of the emission tax revenue is abstracted. While taxes are generally first-best, Tombe and Winter (2015) summarizes the following factors that favor intensity standards: market power (Li and Shi, 2011), incomplete regulation or leakage (Holland, 2012), learning-by-doing in production (Gerlagh and Van der Zwaan, 2006), pre-existing tax distortions (Parry and Williams III, 2012), unexpected productivity shocks (Fischer and Springborn, 2011). This subsection contributes to this literature by highlighting that the political concern is one of the factors favoring an intensity standard over an emission tax.

4.5 Revenue-Neutral Emission Tax

Next, we consider revenue-neutral emission taxes: an emission tax is levied on dirty-good producers, and the tax revenue is redistributed to the two sectors. We derive general analytical results about whether a revenue-neutral emission tax policy is more politically feasible than the per-unit emission tax policy, the intensity standard policy, and the null policy. While policies of this kind are the topic of many recent studies (Goulder, 1995; Parry, 1995; Parry and Bento, 2000; Chiroleu-Assouline and Fodha, 2006; Bento and Jacobsen, 2007;

Dissou and Sun, 2013; Chan and Yip, 2018b; Hafstead and Williams III, 2018; Yip, 2018), our analytical results are the first to compare this policy to other environmental policies using the criteria in Definition 2.

Denote $\mathcal{RN}(\tau, h_j)$ as a revenue-neutral emission taxation scheme with the tax revenue redistributed to subsidize each filled job in sector j by h_j dollars in a lump-sum fashion. Since this policy is revenue-neutral, h_c and h_d satisfy the following budget constraint:

$$\phi^{\mathcal{RN}}(\tau, h_j)\tau x^{\mathcal{RN}}(\tau, h_j) = (1 - \phi^{\mathcal{RN}}(\tau, h_j))h_c + \phi^{\mathcal{RN}}(\tau, h_j)h_d. \quad (26)$$

Taking h_j as given, the asset values of filled jobs are

$$\begin{aligned} rJ_d^F &= \max_{x\in[0,\bar{x}]} \left\{ p_d A - w_d - C(\bar{x} - x) - \tau + h_d + \lambda(J_d^V - J_d^F) \right\} \text{ and} \\ rJ_c^F &= p_c A - w_c + h_c + \lambda(J_c^V - J_c^F). \end{aligned} \quad (27)$$

A revenue-neutral emission tax $\mathcal{RN}(\tau, h_j)$ reduces the intensive margin of emission the same way as a per-unit emission tax $\mathcal{ET}(\tau)$. Hence, taking h_j as given, the optimal emission level $x^{\mathcal{RN}}(\tau, h_j)$ solves the first-order condition (23) (i.e., $x^{\mathcal{RN}}(\tau, h_j) = x^{\mathcal{ET}}(\tau)$). The wage equations are given by

$$\begin{aligned} w_d &= (1 - \beta)rJ^U + \beta\Big(p_d A - C(\bar{x} - x) - \tau x - rk + h_d\Big) \text{ and} \\ w_c &= (1 - \beta)rJ^U + \beta\Big(p_c A - rk + h_c\Big). \end{aligned} \quad (28)$$

Using equations (7), (9), (27), and (28), the two zero-profit conditions are given by

$$\begin{aligned} rk &= \frac{q(\theta)(1-\beta)}{r+\lambda}\left(p_d(\phi)A - C(\bar{x} - x) - \tau x - z - rk\left(1 + \frac{\theta\beta}{1-\beta}\right) + h_d\right) \text{ and} \\ rk &= \frac{q(\theta)(1-\beta)}{r+\lambda}\left(p_c(\phi)A - z - rk\left(1 + \frac{\theta\beta}{1-\beta}\right) + h_c\right). \end{aligned} \quad (29)$$

The revenue differential can be expressed as follows:

$$\begin{aligned} \Lambda(\phi^{\mathcal{RN}}(\tau, h_j)) &\equiv p_d(\phi^{\mathcal{RN}}(\tau, h_j))A - p_c(\phi^{\mathcal{RN}}(\tau, h_j))A \\ &= C(\bar{x} - x^{\mathcal{RN}}(\tau, h_j)) + \tau x^{\mathcal{RN}}(\tau, h_j) + h_c - h_d, \end{aligned} \quad (30)$$

where h_c and h_d satisfy the budget constraint (26).[11] With the same emission level from the intensive margin, the abatement cost and the emission tax payment is identical under $\mathcal{RN}(\tau, h_j)$ and $\mathcal{ET}(\tau)$. Hence, the revenue differential under $\mathcal{ET}(\tau)$ equals $C(\bar{x} -$

[11] It is straightforward to show the existence of the unique steady-state equilibrium and thus the proof is omitted for space consideration.

$x^{\mathcal{RN}}(\tau, h_j)) + \tau x^{\mathcal{RN}}(\tau, h_j)$. Mathematically, we have

$$\begin{aligned} p_d(\phi^{\mathcal{ET}}(\tau))A - p_c(\phi^{\mathcal{ET}}(\tau))A &= C(\bar{x} - x^{\mathcal{RN}}(\tau, h_j)) + \tau x^{\mathcal{RN}}(\tau, h_j) \text{ and thus} \\ p_d(\phi^{\mathcal{RN}}(\tau, h_j))A - p_c(\phi^{\mathcal{RN}}(\tau, h_j))A &= p_d(\phi^{\mathcal{ET}}(\tau))A - p_c(\phi^{\mathcal{ET}}(\tau))A + h_c - h_d. \end{aligned}$$

If $h_c \geq h_d$, it is less beneficial to open up vacancies in the polluting sector under $\mathcal{RN}(\tau, h_j)$ than $\mathcal{ET}(\tau)$. As a result, $\phi^{\mathcal{RN}}(\tau, h_j) \leq \phi^{\mathcal{ET}}(\tau)$ and thus $p_d(\phi^{\mathcal{RN}}(\tau, h_j)) \geq p_d(\phi^{\mathcal{ET}}(\tau))$. Using $p_d(\phi^{\mathcal{RN}}(\tau, h_j)) \geq p_d(\phi^{\mathcal{ET}}(\tau))$, one can show that if $h_d > 0$, the following inequalities follow:

$$0 < p_d(\phi^{\mathcal{RN}}(\tau, h_j)) - p_d(\phi^{\mathcal{ET}}(\tau)) + h_d = p_c(\phi^{\mathcal{ET}}(\tau)) + h_c - p_c(\phi^{\mathcal{RN}}(\tau, h_j)).$$

$p_c(\phi^{\mathcal{ET}}(\tau)) + h_c > p_c(\phi^{\mathcal{RN}}(\tau, h_j))$ guarantees that the flow profit of clean-good jobs is higher under $\mathcal{RN}(\tau, h_j)$ than $\mathcal{ET}(\tau)$. A direct comparison between the zero-profit conditions of clean-good jobs (15) and (27) suggests that market tightness is higher under $\mathcal{RN}(\tau, h_j)$ than $\mathcal{ET}(\tau)$. Hence, $u^{\mathcal{RN}}(\tau, h_j) < u^{\mathcal{ET}}(\tau)$. The following proposition summarizes the result.

Proposition 7. *Given any emission tax $\tau > 0$, if $h_c \geq h_d > 0$, $\mathcal{RN}(\tau, h_c, h_d)$ is EE preferred to $\mathcal{ET}(\tau)$.*

The condition $h_c \geq h_d$ ensures that it is more profitable to create vacancies in the nonpolluting sector, lowering the market share of dirty-good jobs and thus the extensive margin of emission. Notice that emission along its intensive margin is identical under the two policies. On the basis of the criteria (19), the environmental quality is better under $\mathcal{RN}(\tau, h_j)$ than $\mathcal{ET}(\tau)$.

With the higher market share of the nonpolluting sector, the price of clean goods are lower under $\mathcal{RN}(\tau, h_j)$ than $\mathcal{ET}(\tau)$. The condition $h_d > 0$ restricts the revenue differential being so large that the reduction in the price of clean goods will bring down the flow profits in the nonpolluting sector even in the presence of subsidies h_c. In other words, $h_d > 0$ ensures it is more beneficial to create jobs under $\mathcal{RN}(\tau, h_j)$ than $\mathcal{ET}(\tau)$ so that the unemployment rate is lower under $\mathcal{RN}(\tau, h_j)$.

Next, we compare the political feasibility between $\mathcal{RN}(\tau, h_j)$ and $\varnothing$. The introduction of a revenue-neutral emission tax $\mathcal{RN}(\tau, h_j)$ to a laissez-faire equilibrium reduces the intensive margin of emission the same way as a per-unit emission tax $\mathcal{ET}(\tau)$. From Lemma 1 and the discussion above, $x^{\mathcal{RN}}(\tau, h_j) = x^{\mathcal{ET}}(\tau) < x^{\varnothing}$. If the tax revenue is equally rebated to each job (i.e., $h_c = h_d$), the revenue differential will be identical under the two policies and thus $\phi^{\mathcal{RN}}(\tau, h_c) = \phi^{\mathcal{ET}}(\tau) < \phi^{\varnothing}$. Therefore, a revenue-neutral emission tax, in general, results in a lower level of emission per output than a laissez-faire equilibrium (i.e., $\varphi^{\mathcal{RN}}(\tau, h_c) < \varphi_{\varnothing}$). The following proposition states that under certain circumstances, there always exists a $\tau \in \mathbb{R}_{++}$ such that the introduction of a revenue-neutral emission tax to a laissez-faire equilibrium also reduces the unemployment rate. Under these circumstances, there always exists an emission tax $\tau \in \mathbb{R}_{++}$ such that $\mathcal{RN}(\tau, h_c)$ is EE preferred to $\varnothing$.

Proposition 8. *If $\varepsilon_{p_d,\phi} \leq \varepsilon_{p_c,1-\phi}$ in a laissez-faire equilibrium, there always exists $\tau \in \mathbb{R}_{++}$ such that $\mathcal{RN}(\tau, h_j)$ is EE preferred to $\varnothing$, where $h_c = h_d$, and $\varepsilon_{p_d,\phi} \equiv \phi \frac{\partial p_d A}{\partial \phi}$ and $\varepsilon_{p_c,1-\phi} \equiv (1-\phi)\frac{\partial p_c A}{\partial(1-\phi)}$ are the partial elasticities of revenue with respect to respective market share.*

Proof. See Appendix 7.2. □

Intuitively, the introduction of an emission tax under $\mathcal{RN}(\tau, h_c)$ increases the flow cost of dirty-good jobs, depressing the market share of the polluting sector. As the clean goods become relatively more abundant, there is a downward general equilibrium effect on the price of clean goods. This general equilibrium effect depresses the supply of clean-good vacancies and thus increases the unemployment rate. On the other hand, the transfer to filled jobs induces the supply of vacancies in both sectors, causing the unemployment rate to fall. Therefore, whether unemployment increases under $\mathcal{RN}(\tau_x)$ relative to the null policy is inconclusive, dependent on the elasticities of revenues with respective to the market share. The condition stated in Proposition 8 ensures that the responsiveness of the revenue of clean goods with respect to the emission tax is low. As such, the decrease in the flow profit in clean-good jobs from the negative general equilibrium effect is so small that this negative effect is outweighed by the direct effect of the transfer on their flow profit. Hence, the stated condition in Proposition 8 ensures that the introduction of a revenue-neutral emission tax will lower unemployment so that $\mathcal{RN}(\tau, h_j)$ is EE preferred to $\varnothing$.

Often policymakers encounter political forces because of potential job losses from proposed environmental policies. Proposition 8 provides an empirically testable condition to ease this political concern. Moreover, this condition is testable ex ante so that policymakers could know whether there exists an EE preferable $\mathcal{RN}(\tau, h_j)$ prior to the implementation of the policy. Furthermore, the condition requires only two sufficient statistics, which are easily acquired without solving a structural model (Chetty, 2009). If the condition is satisfied, Proposition 9 states that this policy $\mathcal{RN}(\tau, h_j)$ could be EE preferred to intensity standards as well for a certain interval of the standard.

Proposition 9. *If $\varepsilon_{p_d,\phi} \leq \varepsilon_{p_g,1-\phi}$ in a laissez-faire equilibrium, $\mathcal{RN}(\tau, h_j)$ is EE preferred to $\mathcal{IS}(\hat{x}(\tau))$ for all $\tau \in \Theta$ and $\hat{x}(\tau) \in [x^{\mathcal{RN}}(\tau), \bar{x}]$, where Θ is the collection of τ such that $\mathcal{RN}(\tau, h_j)$ is EE preferred to $\varnothing$, and $h_c = h_d$.*

Proof. See Appendix 7.3. □

5 Welfare Analysis

This section performs welfare analysis of environmental policies. The results pertain to designing socially optimal policies. In previous sections, our analysis restricts to finding "better" policies under the "EE preference" criteria and refrains from ranking policies that are not EE preferred to each other. We undertake this task in this section.

5.1 Welfare Function

We define welfare as the sum of total steady-state surplus and the value of the aggregate emission level. The use of total steady-state surplus as a measure of welfare is common in the search and matching literature (Hosios, 1990; Pissarides, 2000). We give this welfare function a novel use by extending it to include the level of pollutant emission. Welfare can be written as

$$W = (1-u)[\phi J_d^E + (1-\phi)J_g^E] + uJ^U + (1-u)[\phi J_d^F + (1-\phi)J_g^F] + v[\phi J_d^V + (1-\phi)J_g^V] - \eta\frac{\chi}{r},$$

where $\eta \geq 0$ captures the relative value of emission, and $\eta\chi/r$ denotes the present value of the social cost of emission. Efficient allocation maximizes welfare subject to equation (10). Hence, we can simplify the welfare function as follows:[12]

$$W = \frac{1}{r}\left[uz + (1-u)\Big(\phi\big(p_d A - C(\bar{x}-x) - \eta x\big) + (1-\phi)p_c A\Big)\right]. \tag{31}$$

That is, welfare is a weighted sum of values: the flow value of unemployment z weighted by u, the flow value of dirty-good production (net of the detriment of pollutant emission and the cost of abatement) weighted by $(1-u)\phi$, and the flow value of clean-good production weighted by $(1-u)(1-\phi)$. A social planner chooses (x, θ, ϕ) to maximize the welfare function (31) subject to the steady-state unemployment (10). Since u is the function of θ and is strictly monotone with θ, the social planner's problem can be further reduced to

$$W^* = \max_{x\in[0,\bar{x}],(u,\phi)\in[0,1]^2}\left\{uz + (1-u)\Big(\phi\big(p_d A - C(\bar{x}-x) - \eta x\big) + (1-\phi)p_c A\Big)\right\}. \tag{32}$$

Let superscript W denote the socially optimal object. Differentiating the welfare function with respect to x, the first-order condition is

$$\frac{\partial W}{\partial x} = C'(\bar{x} - x^W) - \eta = 0. \tag{33}$$

That is, the socially optimal level of emission per job x^W equates the marginal social benefit of abatement to its marginal social cost. To abate an additional unit of emission, the society

[12]Proof is provided in Appendix 7.4.

pays the marginal cost $C'(\bar{x}-x^W)$. Meanwhile, this additional unit of abatement reduces a unit of the social cost of emission η.

Differentiating the welfare function with respect to ϕ, the first-order condition is

$$\frac{\partial W}{\partial \phi} = p_d(\phi^W)A - C(\bar{x}-x) - \eta x - p_c(\phi^W)A + \varepsilon_{p_d,\phi}(\phi^W) - \varepsilon_{p_c,1-\phi}(\phi^W) = 0. \quad (34)$$

Shifting an additional unit of production from the nonpolluting sector to the polluting sector generates the market value by $p_d(\phi^W)A - C(\bar{x}-x)$. Since clean goods become less abundant, the market value of all existing clean-good production rises by $\varepsilon_{p_c,1-\phi}(\phi^W)$. Meanwhile, the shift of the production brings three social costs to the economy. First, it reduces the production value of the additional unit of the clean goods by $p_c(\phi^W)A$. Second, this additional unit of dirty-good jobs generates emission level x along the extensive margin and costs the society by ηx. Since dirty goods become more abundant, the market value of all existing dirty-good production falls by $\varepsilon_{p_d,\phi}(\phi^W)$. Again, the optimal market share equates the two marginal social benefits to its three marginal social costs.

Differentiating the welfare function with respect to ϕ, we have

$$\frac{\partial W}{\partial u} = z - \Big[\phi\big(p_d(\phi)A - c(\bar{x}-x) - \eta x\big) + (1-\phi)p_g(\phi)A\Big].$$

The economy gains the flow value of unemployment z for an additional unit of unemployment. Meanwhile, it loses the average market value of employment. Since the flow value of a filled job in either sector exceeds the flow value of unemployment, $\partial W/\partial u > 0$. In other words, it is always beneficial to an economy to lower unemployment.

The social optimality and the political feasibility are two highly relevant concepts. First, a more politically feasible policy must not lose welfare because of the lower level of unemployment. Second, a more politically feasible policy may lose welfare from other two dimensions: the intensive and the extensive margins of emission. For example, any political feasible policy may over-abate emission to yield lower emission per output. In this example, the society pays too much an abatement cost. Third, a welfare-improving policy could be politically infeasible. There exist tons of policies that yield higher social welfare, relative to the null policy, but increase unemployment. Hence, the social optimality and the political feasibility do not imply each other; instead, they complement each other in selecting policies that are welfare-improving and politically feasible.

It is clear to see the sources of externalities in an economy from equations (33), (34), and (35), representing the intensive margin, the extensive margin, and the scale effect discussed in Section 3. First, there is the direct environmental externality from the production process in each worker-firm pair (inefficient x). Polluters are not required to pay the social cost of emission in the absence of environmental policies.

Second, there is the job allocation externality (inefficient ϕ). The intuition is that posting a vacancy for producing either good changes the aggregate job composition, which has chain effects on the production values of the two goods. For example, if $\varepsilon_{p_d,\phi}(\phi^W) > \varepsilon_{p_c,1-\phi}(\phi^W)$, an additional market share of dirty-good jobs reduces the value of the preexisting dirty goods more than the increase in the value of clean goods. This price effect is not considered in the creation of vacancies of either type.

Finally, there is the vacancy entry/exit externality (inefficient u). The intuition is that the entry/exit of a vacancy changes labor market tightness, which would cause ripple effects on aggregate matching probabilities. Externality arises when firms do not consider the effect of their action on the aggregate matching probabilities. The latter two externalities translate into environmental externality through the composition effect and the scale effect under the production externality formulation.

5.2 Optimal Environmental Policies

Next, we investigate the optimality of per-unit emission tax policies, intensity standard policies, and revenue-neutral emission tax policies. This investigation is informative for two reasons. First, it is relevant to policymakers in selecting among these policies. Second, these investigations complete the analysis on the characterization of socially optimal and politically feasible environmental policies.

From equation (33), a social planner could impose a Pigouvian tax on emission so that a per-unit emission tax policy $\mathcal{ET}(\eta)$ equates the marginal social cost of emission to its marginal social benefit. In this case, the emission per dirty-good job $x^{\mathcal{ET}}(\eta)$ equals x^W. The corresponding $\phi^{\mathcal{ET}}(\eta)$ solves the revenue differential given by $\Lambda(\phi^{\mathcal{ET}}(\eta)) = C(\bar{x} - x^{\mathcal{ET}}(\eta)) + \eta x^{\mathcal{ET}}(\eta)$. According to equation (34), the derivative of the welfare with respect to ϕ evaluated at $\phi^{\mathcal{ET}}(\eta)$ can be expressed as follows:

$$\left.\frac{\partial W}{\partial \phi}\right|_{\phi=\phi^{\mathcal{ET}}(\eta)} = \varepsilon_{p_d,\phi}(\phi^{\mathcal{ET}}(\eta)) - \varepsilon_{p_c,1-\phi}(\phi^{\mathcal{ET}}(\eta)).$$

$\mathcal{ET}(\eta)$ could be optimal only if $\varepsilon_{p_d,\phi}(\phi^{\mathcal{ET}}(\eta)) = \varepsilon_{p_c,1-\phi}(\phi^{\mathcal{ET}}(\eta))$; nevertheless, there exists no reason to believe that these two elasticities are identical at $\phi^{\mathcal{ET}}(\eta)$. Whereas emission per output is socially optimal under $\mathcal{ET}(\eta)$, the externality on the job composition is unlikely internalized. This policy improves welfare by reducing the intensive margin of emission but could further distort the job composition, dependent on the two elasticities. Moreover, Lemma 1 indicates that this policy increases unemployment, reducing welfare. It is therefore uncertain whether the introduction of a per-unit emission tax to a laissez-faire equilibrium improves welfare or not. Similar arguments can be applied to reach the same conclusion under $\mathcal{IS}(x^{ET}(\eta))$.

Next, we investigate the welfare of the revenue-neutral emission tax policy $\mathcal{RN}(\eta, h_j)$, in which a social planner imposes an emission tax η per unit of x so that the intensive margin of emission is socially optimal. Moreover, this policy rebates h_d to each dirty-good job, and rebates the rest of the emission tax revenue to each clean-good job. The total emission tax revenue equals $\eta x^W \phi(1-u)$; therefore, $h_d \in [0, \eta x^W \phi(1-u)]$. A revenue-neutral emission tax policy requires the rest of the tax revenue is rebated to each clean-good job, equal to $h_c = (\eta x^W \phi - h_d \phi)/(1-\phi)$.

To attain the social optimum (i.e., the $\phi^{\mathcal{RN}}(\eta, h_j)$ satisfies equation (34)), the rebate differential should be set to $\varepsilon_{p_d,\phi}(\phi^{\mathcal{RN}}(\eta, h_j)) - \varepsilon_{p_c,1-\phi}(\phi^{\mathcal{RN}}(\eta, h_j))$ as follows:

$$h_d - \frac{\eta x^W \phi^{\mathcal{RN}}(\eta, h_j) - h_d \phi^{\mathcal{RN}}(\eta, h_j)}{1 - \phi^{\mathcal{RN}}(\eta, h_j)} = \varepsilon_{p_d,\phi}(\phi^{\mathcal{RN}}(\eta, h_j)) - \varepsilon_{p_c,1-\phi}(\phi^{\mathcal{RN}}(\eta, h_j)).$$

The interior solution of h_d is given by $\eta x^W \phi^{\mathcal{RN}} + (1-\phi^{\mathcal{RN}})[\varepsilon_{p_d,\phi}(\phi^{\mathcal{RN}}) - \varepsilon_{p_c,1-\phi}(\phi^{\mathcal{RN}})]$ and the corresponding rebate to each clean-good job is given by $\eta x^W \phi^{\mathcal{RN}} - \phi^{\mathcal{RN}}[\varepsilon_{p_d,\phi}(\phi^{\mathcal{RN}}) - \varepsilon_{p_c,1-\phi}(\phi^{\mathcal{RN}})]$.

This policy reaps a double dividend. First, it improves the environmental quality. This policy corrects the private emission cost per job; it internalizes the externality of emission by setting the Pigouvian tax on emission. Second, the tax revenue is recycled to fine-tune the job composition, the distortion of the labor market. As highlighted above, the entry in either sector does not consider the effect of its entry on the relative prices, generating an externality on the existing jobs. This policy corrects this externality by redistributing the emission tax revenue such that the private costs of creating vacancies internalize the externality.

The rebate of the tax revenue depends largely on the elasticity of revenue. Suppose $\varepsilon_{p_d,\phi}(\phi^{\mathcal{RN}}) - \varepsilon_{p_c,1-\phi}(\phi^{\mathcal{RN}}) < 0$. That is, the elasticity of revenue is larger in the polluting sector. This economy is better off shrinking the market share of the polluting sector because the increase in the total revenue in the polluting sector outweighs the decrease in the total revenue in the other sector. This explains why a social planner will rebate less to each dirty-good job if $\varepsilon_{p_d,\phi}(\phi^{\mathcal{RN}}) - \varepsilon_{p_c,1-\phi}(\phi^{\mathcal{RN}}) < 0$. The rebates should be evenly distributed regardless of sector only if $\varepsilon_{p_d,\phi}(\phi^{\mathcal{RN}}) = \varepsilon_{p_c,1-\phi}(\phi^{\mathcal{RN}})$.

Since $s_h \in [0, \eta x^W \phi^{\mathcal{RN}}(1-u^{\mathcal{RN}})]$, one can show that the general solution of the rebate to each dirty-good job is given by

$$h_d = \begin{cases} 0, & \text{if } -\frac{\eta x^W \phi^{\mathcal{RN}}}{1-\phi^{\mathcal{RN}}} > \varepsilon_{p_d,\phi} - \varepsilon_{p_g,1-\phi}; \\ \eta x^W \phi^{\mathcal{RN}} + (1-\phi^{\mathcal{RN}})[\varepsilon_{p_d,\phi} - \varepsilon_{p_g,1-\phi}], & \text{if } -\frac{\eta x^W \phi^{\mathcal{RN}}}{1-\phi^{\mathcal{RN}}} \leq \varepsilon_{p_d,\phi} - \varepsilon_{p_c,1-\phi} \leq \eta x^W; \\ \eta x^W, & \text{if } \varepsilon_{p_d,\phi} - \varepsilon_{p_c,1-\phi} > \eta x^W. \end{cases} \tag{35}$$

The corresponding rebate to each clean-good job is given by

$$h_c = \begin{cases} \frac{\eta x^W \phi^{\mathcal{RN}}}{1-\phi^{\mathcal{RN}}}, & \text{if } -\frac{\eta x^W \phi^{\mathcal{RN}}}{1-\phi^{\mathcal{RN}}} > \varepsilon_{p_d,\phi} - \varepsilon_{p_c,1-\phi}; \\ \eta x^W \phi^{\mathcal{RN}} - (1-\phi^{\mathcal{RN}})[\varepsilon_{p_d,\phi} - \varepsilon_{p_g,1-\phi}], & \text{if } -\frac{\eta x^W \phi^{\mathcal{RN}}}{1-\phi^{\mathcal{RN}}} \leq \varepsilon_{p_d,\phi} - \varepsilon_{p_c,1-\phi} \leq \eta x^W; \\ 0, & \text{if } \varepsilon_{p_d,\phi} - \varepsilon_{p_c,1-\phi} > \eta x^W. \end{cases} \tag{36}$$

Intuitively, $\varepsilon_{p_d,\phi} - \varepsilon_{p_c,1-\phi} < -\eta x^W \phi^{\mathcal{RN}}/(1-\phi^{\mathcal{RN}})$ implies that the revenue elasticity in the polluting sector is so large that it is beneficial to shrink the market share of the polluting sector. When this elasticity is too large, all the emission tax revenues are rebated to the polluting sector, leaving no rebate to the other sector. In this case, there are still too much the market share of the polluting sector, and the job composition is not socially optimal.

Proposition 10. *For all $\eta \in \mathbb{R}_{++}$, if $-\frac{\eta x \phi}{1-\phi} \leq \varepsilon_{p_d,\phi} - \varepsilon_{p_c,1-\phi} \leq \eta x$, $x^{\mathcal{RN}}(\eta, h_j)$ and $\phi^{RN}(\eta, h_j)$ are socially optimal, where h_d and h_c are given by equations (35) and (36).*

In sum, the intensive margin of emission is socially optimal under all the three policies, $\mathcal{RN}(\eta, h_j)$, $\mathcal{ET}(\eta)$, and $\mathcal{IS}(x^{\mathcal{ET}}(\eta))$. However, the job composition is unlikely socially optimal under $\mathcal{ET}(\eta)$ or $\mathcal{IS}(x^{\mathcal{ET}}(\eta))$. Under $\mathcal{RN}(\eta, h_j)$, the emission tax revenue can be rebated to guarantee the job composition at its optimum under a relatively weak assumption. Recall from Proposition 9 that if $\varepsilon_{p_d,\phi} \leq \varepsilon_{p_c,1-\phi}$ under $\varnothing$, there always exists $\tau > 0$ such that $\mathcal{RN}(\tau, h_j)$ is politically feasible. This paper contributes to the literature by highlighting the importance of the revenue elasticities in these two sectors when the social optimality and the political feasibility of environmental policies are studied. Indeed, Propositions 9 and 10 do not imply $\mathcal{RN}(\tau, h_j)$ is, in general, both politically feasible and socially optimal. However, if $\varepsilon_{p_d,\phi} \leq \varepsilon_{p_c,1-\phi}$ under $\varnothing$ is satisfied, the introduction of $\mathcal{RN}(\tau, h_j)$ with a mild τ to a laissez-faire equilibrium will have no significant impact on the two revenue elasticities, and thus the corresponding condition in Proposition 10 is likely satisfied. In other words, once $\varepsilon_{p_d,\phi} \leq \varepsilon_{p_c,1-\phi}$ is satisfied in a laissez-faire equilibrium, the introduction of $\mathcal{RN}(\tau, h_j)$ with a mild τ is, though not necessarily socially optimal, likely welfare-improving and politically feasible.

6 Conclusion

This paper constructs a two-sector search equilibrium model to analyze the unemployment effects of two broad classes of environmental policies, including (but not limited to) a lump-sum tax, a simple per-unit emission tax, an intensity standard, and a revenue-neutral emission tax. We show that the class of policies that only impose a higher flow cost on the polluting sector without providing any incentive to increase emission from an intensive margin is not more politically feasible than a laissez-faire equilibrium, and vice versa. This is the direct implication of the inevitable tradeoff between unemployment and the extensive margin of emission.

To break the inevitability of the tradeoff requires a policy to affect the flow cost of production in both the polluting and the nonpolluting sectors. A revenue-neutral emission tax with equal rebates to both sectors and a proper tax rate is shown to improve both employment and environmental outcomes relative to the laissez-faire equilibrium under the condition that the revenue elasticity in the polluting sector is larger than that in the nonpolluting in absolute value. We show that on the grounds of employment and environmental quality, there always exist intensity standards that are more politically feasible than any emission tax if the tax revenue is not considered, and for any intensity standard, there exists no emission tax that is superior. A revenue-neutral emission tax with the proper rebates to both sectors can be more politically feasible than the simple emission tax without rebates. Under the same condition of the revenue elasticity, such a revenue-neutral emission tax can also be more politically feasible than intensity standards.

Concerning welfare, a Pigouvian tax corrects the environmental externality regarding the emission from each polluting firm but not the job allocation externality in the labor market. Thus, a Pigouvian tax cannot achieve the socially optimal allocation of production between sectors. To internalize the job allocation externality, the tax revenue could be rebated to both sectors such that the rebate differential equals the revenue elasticity differential. Under certain conditions on the revenue elasticity differential, the revenue-neutral Pigouvian tax with rebates can achieve socially optimal allocation of production between sectors.

This paper opens up many potential directions of extensions for future research. First, it would be interesting to explore whether the emission tax revenue can be rebated properly to resolve other externalities in the search economy. For example, we can incorporate the entry/exit externality of unemployed workers by adding an out-of-labor-force status for workers. Second, we can model worker heterogeneity in human capital and firm heterogeneity in productivity to analyze the effects of environmental policies on a wage distribution. Third, we can introduce dynamic stochasticity of productivity to incorporate real business cycle analysis and compare the political feasibility of environmental policies in recessions and booms and also extend the political feasibility criterion on unemployment from the level of unemployment to the volatility of unemployment. Finally, it would be useful to empirically estimate the revenue elasticities in both the polluting and the nonpolluting sectors as functions of the polluting sectors market share. These functions can provide valuable information for testing the condition for one policy to be superior to other policies according to the analysis of this paper or the condition for socially optimal allocation of sectors and predicting the effect of a proposed policy without solving a structural model.

7 Appendix: Proof

7.1 Proof of Proposition 1

We show that a unique ϕ^* exists. Since $\lim_{\phi\to 0}\Lambda(\phi)=\infty$, $\lim_{\phi\to 1}\Lambda(\phi)=\infty$, and $\Lambda(\phi)$ is continuous on $(0,1)$, there must exist at least one $\phi^*\in(0,1)$ such that $\Lambda(\phi^*)=0$ from revenue differential (16). Since $\Lambda'(\phi)<0$ and the R.H.S. is independent of ϕ, the

$\phi^* \in (0, 1)$ is unique. Given the unique ϕ^*, the unique $p_d(\phi^*)$ and $p_c(\phi^*)$ are pinned down by equation (11).

Lastly, we show that a unique θ^* exists. When θ tends to zero, the R.H.S. of equation (15) approaches positive infinity because of $\lim_{\theta\to 0} q(\theta) = \infty$. When θ tends to positive infinity, its R.H.S. approaches negative infinity because of $\lim_{\theta\to\infty} q(\theta) = 0$ and $\lim_{\theta\to\infty} \theta q(\theta) = \infty$. As the L.H.S. is a positive constant, the intermediate value theorem ensures that there exists at least one $\theta^* > 0$ such that equation (15) is satisfied. Since the R.H.S. strictly decreases with θ, θ^* is unique. Substituting the unique θ^* into equation (10) yields the unique steady state u^* because u strictly decreases with θ. Given that x^*, ϕ^*, $p_d(\phi^*)$, $p_c(\phi^*)$, θ^*, and u^* are unique, it is straightforward to complete the rest of the proof.

7.2 Proof of Proposition 8

First, $\varphi^{\mathcal{RN}}(\tau, h_j) = \varphi^{\mathcal{ET}}(\tau) < \varphi^{\varnothing}$ for all $\tau > 0$, where the last inequality follows from Lemma 1. Hence, it is sufficient to show that $\varepsilon_{p_d,\phi} \leq \varepsilon_{p_c,1-\phi}$ implies $\frac{du^{\varnothing}}{d\tau} \leq 0$.

Next, we define

$$\Pi_c^{\mathcal{RN}} \equiv p_c(\phi^{\mathcal{RN}}(\tau, h_c))A - rk - z - \frac{\beta\theta^{\mathcal{RN}}(\tau, h_c)}{1+\beta} rk + \tau x^{\mathcal{RN}}(\tau, h_c)\phi^{\mathcal{RN}}(\tau, h_c).$$

According to the steady-state unemployment (10) and the zero-profit condition in the nonpolluting sector (29), we can claim that

$$\frac{d\Pi_c^{\mathcal{RN}}}{d\tau} \gtreqless 0 \text{ iff } \frac{du^{\mathcal{RN}}}{d\tau} \lesseqgtr 0.$$

Suppose $d\Pi_c^{\mathcal{RN}}/d\tau > 0$. The zero-profit condition in the nonpolluting sector (29) ensures that $d\theta^{\mathcal{RN}}/d\tau > 0$. Using the steady-state unemployment rate (10), it is straightforward to show that $du^{\mathcal{RN}}/d\tau < 0$. Similar arguments can be applied to establish the claim.

Totally differentiating $\Pi_c^{\mathcal{RN}}$ with respect to τ, we have

$$\frac{d\Pi_c^{\mathcal{RN}}}{d\tau} = \frac{dp_c(\phi^{\mathcal{RN}})A}{d\tau} + \frac{d\theta^{\mathcal{RN}}}{d\tau}\frac{\beta}{1+\beta} rk + x^{\mathcal{RN}}\phi^{\mathcal{RN}} + \tau\phi^{\mathcal{RN}}\frac{dx^{\mathcal{RN}}}{d\tau} + \tau x^{\mathcal{RN}}\frac{d\phi^{\mathcal{RN}}}{d\tau}.$$

Note that $|\lim_{\tau\to 0}\frac{dx^{\mathcal{RN}}}{d\tau}| < \infty$ and $|\lim_{\tau\to 0}\frac{d\phi^{\mathcal{RN}}}{d\tau}| < \infty$. Hence, we have

$$\lim_{\tau\to 0}\frac{d\Pi_c^{\mathcal{RN}}}{d\tau} = \lim_{\tau\to 0}\frac{dp_g(\phi^{\mathcal{RN}})A}{d\tau} - \lim_{\tau\to 0}\frac{d\theta^{\mathcal{RN}}}{d\tau}\frac{\beta}{1+\beta} rk + \lim_{\tau\to 0} x^{\mathcal{RN}}\phi^{\mathcal{RN}}.$$

Next, we claim that

$$\lim_{\tau\to 0}\frac{d\Pi_c^{\mathcal{RN}}}{d\tau} \gtreqless 0 \text{ iff } \lim_{\tau\to 0}\frac{dp_c(\phi^{\mathcal{RN}})A}{d\tau} + \lim_{\tau\to 0} x^{\mathcal{RN}}\phi^{\mathcal{RN}} \gtreqless 0.$$

Suppose $\lim_{\tau\to 0}\frac{d\Pi_c^{\mathcal{RN}}}{d\tau}>0$. If the claim is invalid, then $\lim_{\tau\to 0}\frac{dp_g(\phi^{\mathcal{RN}})A}{d\tau}+\lim_{\tau\to 0}x^{\mathcal{RN}}\phi^{\mathcal{RN}}\leq 0$. Using equation (30), we can show that $\lim_{\tau\to 0}\frac{d\Pi_c^{\mathcal{RN}}}{d\tau}>0$ implies $\lim_{\tau\to 0}\frac{d\theta^{\mathcal{RN}}}{d\tau}\frac{\beta}{1+\beta}rk>0$. Hence, we have

$$\lim_{\tau\to 0}\frac{d\Pi_c^{\mathcal{RN}}}{d\tau}=\underbrace{\lim_{\tau\to 0}\frac{dp_g(\phi^{\mathcal{RN}})A}{d\tau}+\lim_{\tau\to 0}x^{\mathcal{RN}}\phi^{\mathcal{RN}}}_{\text{Nonpositive}}-\underbrace{\lim_{\tau\to 0}\frac{d\theta^{\mathcal{RN}}}{d\tau}\frac{\beta}{1+\beta}rk}_{\text{Positive}}<0.$$

A contradiction arises. Hence, $\lim_{\tau\to 0}\frac{d\Pi_c^{\mathcal{RN}}}{d\tau}>0$ implies $\lim_{\tau\to 0}\frac{dp_g(\phi^{\mathcal{RN}})A}{d\tau}+\lim_{\tau\to 0}x^{\mathcal{RN}}\phi^{\mathcal{RN}}>0$. Similar arguments can be applied to establish the claim. Following the two claims in this proof,

$$\lim_{\tau\to 0}\frac{dp_c(\phi^{\mathcal{RN}})A}{d\tau}+\lim_{\tau\to 0}x^{\mathcal{RN}}\phi^{\mathcal{RN}}\gtreqqless 0 \text{ iff } \lim_{\tau\to 0}\frac{du^{\mathcal{RN}}}{d\tau}\lesseqqgtr 0.$$

Next, we derive the sufficient and necessary condition to have $\lim_{\tau\to 0}\frac{dp_c(\phi^{\mathcal{RN}})A}{d\tau}+\lim_{\tau\to 0}x^{\mathcal{RN}}\phi^{\mathcal{RN}}>0$. Since $x^{\mathcal{RN}}=x^{\mathcal{ET}}$ and $\phi^{\mathcal{RN}}=\phi^{\mathcal{ET}}$,

$$\begin{aligned}\lim_{\tau\to 0}\frac{dp_c(\phi^{\mathcal{RN}})A}{d\tau}+\lim_{\tau\to 0}x^{\mathcal{RN}}\phi^{\mathcal{RN}} &> 0\\ \text{implies}\quad \lim_{\tau\to 0}\frac{dp_c(\phi^{\mathcal{ET}})A}{d\phi^{\mathcal{ET}}}\frac{d\phi^{\mathcal{ET}}}{d\tau}+\lim_{\tau\to 0}x^{\mathcal{ET}}\phi^{\mathcal{ET}} &> 0.\end{aligned}$$

Totally differentiating equation (25) with respect to τ, we have $d\phi^{\mathcal{ET}}/d\tau=x^{\mathcal{ET}}[\Lambda(\phi^{\mathcal{ET}})]^{-1}$. The above inequality can therefore be simplified as follows:

$$\begin{aligned}\lim_{\tau\to 0}\frac{dp_c(\phi^{\mathcal{ET}})}{d\phi^{\mathcal{ET}}}\left(\frac{dp_d(\phi^{\mathcal{ET}})}{d\phi^{\mathcal{ET}}}-\frac{dp_c(\phi^{\mathcal{ET}})}{d\phi^{\mathcal{ET}}}\right)^{-1}+\phi^{\mathcal{ET}} &> 0\\ \lim_{\tau\to 0}\varepsilon_{p_d,\phi}(\phi^{\mathcal{ET}}) &< \lim_{\tau_x\to 0}\varepsilon_{p_c,1-\phi}(\phi^{\mathcal{ET}}),\end{aligned}$$

where $\varepsilon_{p_d,\phi}(\phi^{\mathcal{ET}})\equiv\phi^{\mathcal{ET}}\frac{dp_d(\phi^{\mathcal{ET}})A}{d\phi^{\mathcal{ET}}}$ and $\varepsilon_{p_c,1-\phi}(\phi^{\mathcal{ET}})\equiv(1-\phi^{\mathcal{ET}})\frac{dp_c(\phi^{\mathcal{ET}}A)}{d(1-\phi^{\mathcal{ET}})}$. We used $\frac{dp_d(\phi^{\mathcal{ET}})}{d\phi^{\mathcal{ET}}}-\frac{dp_c(\phi^{\mathcal{ET}})}{d\phi^{\mathcal{ET}}}<0$. Since $\lim_{\tau\to 0}\phi^{\mathcal{ET}}=\phi^{\varnothing}$, the inequality can be further simplified to $\varepsilon_{p_d,\phi}(\phi^{\varnothing})<\varepsilon_{p_c,1-\phi}(\phi^{\varnothing})$. A similar argument can be applied to show that

$$\varepsilon_{p_d,\phi}(\phi^{\varnothing})\lesseqqgtr\varepsilon_{p_c,1-\phi}(\phi^{\varnothing}) \text{ iff } \frac{du^{\varnothing}}{d\tau}\lesseqqgtr 0.$$

7.3 Proof of Proposition 9

It is trivial to see that if $\hat{x}=\bar{x}$, Proposition 8 implies Proposition 9. Next, we prove the proposition for all $\hat{x}(\tau)\in[x^{\mathcal{ET}}(\tau),\bar{x})$. Since $h_c=h_d$, $\phi^{\mathcal{RN}}=\phi^{\mathcal{ET}}$. Since $x^{\mathcal{RN}}=x^{\mathcal{ET}}$, $\phi^{\mathcal{RN}}=\phi^{\mathcal{ET}}$ implies $\varphi^{\mathcal{RN}}=\varphi^{\mathcal{ET}}$. For all $\hat{x}(\tau)\in[x^{\mathcal{ET}}(\tau),\bar{x}]$, $x^{\mathcal{IS}}(\hat{x}(\tau))\geq x^{\mathcal{ET}}(\tau)$ and $\phi^{\mathcal{IS}}(\hat{x}(\tau))\geq\phi^{\mathcal{ET}}(\tau)$. Hence, $\varphi^{\mathcal{RN}}(\tau,h_j)=\varphi^{\mathcal{ET}}(\tau)<\varphi^{\mathcal{IS}}(\hat{x}(\tau))$ for all $\hat{x}(\tau)\in$

$[x^{\mathcal{ET}}(\tau), \bar{x}]$.

From Lemma 2, $u^{\mathcal{IS}}(\hat{x}) > u^{\varnothing}$ for all $\hat{x} \in [0, \bar{x})$. Suppose $\varepsilon_{p_d,\phi} \geq \varepsilon_{p_c,1-\phi}$ is satisfied, Proposition 8 implies $u^{\mathcal{RN}}(\tau, h_j) \leq u^{\varnothing}$ for all $\tau \in \Theta$. Hence, $u^{\mathcal{RN}}(\tau, h_j) \leq u^{\mathcal{IS}}(\hat{x}(\tau))$ for all $\hat{x}(\tau) \in [x^{\mathcal{ET}}(\tau), \bar{x})$ and $\tau \in \Theta$.

7.4 Proof of Equation (31)

Using equations (3) and (10), one can show that

$$\begin{aligned}
& (1-u)[\phi r J_d^E + (1-\phi) r J_c^E] + u r J^U \\
= \; & (1-u)[\phi w_d + (1-\phi) w_c] + \lambda(1-u)[\phi(J^U - J_d^E) + (1-\phi)(J^U - J_c^E)] \\
& + uz + u\theta q(\theta)[\phi(J_d^E - J^U) + (1-\phi)(J_c^E - J^U)] \\
= \; & (1-u)[\phi w_d + (1-\phi) w_c] + uz.
\end{aligned}$$

We applies $\lambda(1-u) = u\theta q(\theta)$ from equation (10) to the last line. Using equations (5) and (10), one can show that

$$\begin{aligned}
& (1-u)[\phi J_d^F + (1-\phi) J_c^F] + v[\phi J_d^V + (1-\phi) J_c^V] \\
= \; & (1-u)[\phi J_d^F + (1-\phi) J_c^F] + \theta u[\phi J_d^V + (1-\phi) J_c^V] \\
= \; & -(1-u)[\phi w_d + (1-\phi) w_c] + (1-u)[\phi\,(p_d A - C(\bar{x} - x)) + (1-\phi) p_c A] \\
& + \lambda(1-u)[\phi(J_d^V - J_d^F) + (1-\phi)(J^V - J_c^F)] + u\theta q(\theta)[\phi(J_b^F - J_b^V) + (1-\phi)(J_g^F - J_c^V)] \\
= \; & -(1-u)[\phi w_d + (1-\phi) w_c] + (1-u)[\phi\,(p_d A - C(\bar{x} - x)) + (1-\phi) p_c A].
\end{aligned}$$

Here we also added the abatement cost in the dirty-good jobs. The last line applies $\lambda(1 - u) = u\theta q(\theta)$ from equation (10).

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