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Environmental Policy and Health in the Presence of Labor Market Imperfections

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Abstract

We examine the impact of environmental taxation on health and output, in the presence of labor market frictions, by developing an intertemporal general equilibrium search model of unemployment with pollution and endogenous health-status, which is coherent with the empirical evidence that unemployment is detrimental to health. Amongst several results, we demonstrate that matching process and wage bargaining introduce new channels of transmission of environmental taxation on the economy such that assuming perfect labor market leads to over-estimate the positive impact of environmental taxation on health. Furthermore, we highlight that the existence of a pollution externality on health creates a sort of "rebound effect" of the environmental policy, reducing its efficiency in terms of pollution reduction. We also show that for the most polluted economies (with great room of health improvements), the higher market frictions, the greater the expected health dividend of environmental policy.

1 Introduction

Since more than fifty years, a huge amount of epidemiological literature demonstrated how pollution and global warming are harmful to health. More recently, several theoretical contributions in the field of economics highlighted different mechanisms through which environmental regulation could improve health. Nevertheless, none of these economic contributions took into account the role that labor market could play, while there is a growing empirical evidence that unemployment and firm's layoffs deteriorate physical and mental health.

The aim of this article is to re-examine the health effects of the environmental policy (hereafter EP) in the presence of labor market imperfections. Because environmental preservation could reduce economic activity and therefore increase unemployment, would the health dividend expected from a better environment be reduced by the rise on unemployment or even be reversed? How labor market policies aimed at reducing unemployment affect both pollution emissions and health in the presence of a negative externality of pollution on health?

It is well-established now that pollution and global warming have a negative impact on health, through both morbidity and mortality. Economic literature dealt with this empirical evidence to evaluate the economic impacts of the detrimental effect of pollution on health,[1] and to demonstrate that environmental policy, limiting pollution, could generate a double dividend by improving health[2]

Despite progress in our understanding of the economic mechanisms through which improvements in health could limit the negative impact of environmental policy on the economy, to our best knowledge, not any theoretical contribution deals with the role market labor, especially market labor imbalances, while it could play on the positive influence of the environmental policy on health.[3] On one hand, the existing theoretical articles identified channels of transmission that could be affected by labor market imperfections and as a result the positive impact of environmental policy on health could be altered or even reversed. On other hand, empirical evidence suggest that unemployment affects health and therefore the expected positive effect of environmental policy on health could be over- or under-estimated, in the presence of labor market imperfections.

At the individual level, the negative impact of job loss on individuals' health is becoming well-documented. For example, Sullivan and von Wachter (2009) find

[1]For a general overview of the impact of the environment on health and its impact on human capital, see Graff Zivin and Neidell (2013). For recent empirical contributions, see Chang et al. (2016); Graff Zivin et al. (2018); Chen et al. (2018); Goodman et al. (2018).

[2]For recent theoretical contributions see Bretschger and Vinogradova (2017); Palivos and Varvarigos (2017); Klarl (2016); Chen et al. (2015); Wang et al. (2015).

[3]Note that some articles about environmental policy integrate labor market in their analysis, like the "*double dividend*" literature (for example, see Aubert and Chiroleu-Assouline, 2017). However, few other articles account for labor market imperfections (Ono, 2008; Sanz and Schwartz, 2013; Hafstead and Williams III, 2018; Hafstead et al., 2018, for example) and they do not share the same perspective than us. Hafstead and Williams III (2018) and Hafstead et al. (2018) investigate the effects of environmental policy on unemployment using a search model but they do not take into account the health dimension.

short- and long-term effect of job displacement on mortality hazard using quarterly Pensylvania data covering 1980-2006, focusing on high-seniority male workers. Eliason and Storrie (2009a) study the impact of workers displacement due to firm closures in Sweden in 1987 and 1988. They show that the mortality risk for men rises by 44 percent in the four years after job loss. With the same data, Eliason and Storrie (2009b) find evidence that, during the 12-years following job loss, there exists a significant increase in the risk of hospitalization due to alcohol-related conditions, for men and women, and due to traffic accidents and self-harm for men only. Using administrative data from Denmark in the period 1980-2006, Browning and Heinesen (2012) find that the risk of overall mortality rises of 79% in the year of displacement and remains 11% higher in the 20 years following the replacement, showing that the detrimental impact of job loss on health continues in the long-run. They report an increase in the risk of overall mortality and death from circulatory disease, as well suicide and suicide attempts, death and hospitalization related to traffic accidents, alcohol-related disease and mental illness.[4] Bloemen et al. (2018) use Dutch administrative data for the period 1999-2010 and find that the job loss due to firm disclosure rises the probability of death by 34% in the five years after job loss. The originality of their contribution is that they control for pre-existing differences in firm-level worker characteristics, like health and mortality rate, in order to avoid endogeneity bias. They explain their finding by an increase in the diseases of the circulatory system and by changes in lifestyle. Charles and DeCicca (2008) use data from the National Health Interview Surveys (NHISs) and estimate the impact of local labor market conditions on the measures of health and health behaviors of a sample of individuals living in the largest metropolitan statistical areas in the United States. They report evidence that weight-related health (captured by the body mass index) and mental health deteriorate with the market labor conditions, and that the relationships are stronger for people less educated and for African-american people. All the empirical evidence reported here[5] are explained by the fact that job loss would increase stress and fear of losing job, and/or would have income and wealth effects. They highlight the potential significant impact that market labor imbalances could play in relation between environmental policy and health.

At the aggregate level, several empirical studies found that mortality rate is pro-cyclical and therefore recession is good for health because people would change their health behaviour (for example Ruhm, 2000, 2003, 2015, 2016; Ruhm and Jones, 2012; Dehejia and Lleras-Muney, 2004). As noted by Miller et al. (2009, p.122), "*a typical estimate from the literature suggests that a 1 percentage point increase in a state's unemployment rate is associated with a 0.54 percent reduction in that state's mortality rates.*" Nevertheless, Miller et al. (2009) provide evidence that the improvements in health found during recessions do not come from changes in the employment-status of individuals but rather from external factors. Stevens et al.

[4] Dee (2001), using the annual telephone-based survey responses to the Center for Disease Control 's Behavioral Risk Factor Surveillance for period 1984-1995, also showed that binge drinking rises during downturns, not only for those who lost their jobs but also for those who remained employed. He noted that these results may reflect the influence of economic stress.

[5] For further references, see Kasl and Jones (2000).

(2015) confirm this result finding that "*own-group employment rates are not systematically related to own-group mortality*". Coile et al. (2014) show that for workers in their late 50s or 60s recession could make them temporarily healthier but finally is negative in longer term. Bender et al. (2013) for 11 European countries for period 1971-2001, show that unemployment temporary reduces mortality but increases it in long term. Using data from the Great Recession, Currie et al. (2015) show that recession may have a detrimental impact on mothers self-reported health with an increase in their smoking and drug use. They also find that this impact varies according to whether mothers are hispanic, white, well-educated, less-educated,... All these recent results confirm the conclusion by Modrek et al. (2013) in their synthesis conducted on 172 English language studies published from 1 January 1980 through 1 April 2013: "*We found consistent evidence that recessions, and unemployment in particular, can be significantly damaging to mental health, increasing the risk of substance abuse and suicide particularly for young men. We also found that the previously reported mortality declines during recessions may occur in only a few causes of death such as reduced automobile deaths.*"

According to the aforementioned literature, it appears that there is empirical evidence, at both firm-level and aggregate-level, that a rise in unemployment is detrimental for health.

The present article aims at improving the current theoretical literature on the positive effect of environmental policy on health, by developing a more realistic framework in which market labor shares common features of contemporaneous market labor: unemployment and wage bargaining. For that purpose, we develop an intertemporal general equilibrium model with pollution, endogenous health-status and imperfections on labor market, which is coherent with the environmental evidence that a rise in unemployment is detrimental for health. Pollution is assumed to originate from either final output or physical capital and environmental policy is defined as a tax on the source of pollution.[6] Individual health-status is modeled as in Grossman (1972): it is viewed as a capital in which the agent invests time and medical expenditures, and whose stock depreciates with time. Following Cropper (1981), we assume that pollution increases the depreciation rate. Finally, labor market imperfections are captured through a matching process and a wage bargaining à la Nash, using the framework by Shi and Wen (1997, 1999). More importantly, while we discussed the empirical evidence about the detrimental impact of unemployment in health, we do not assume here that health-status is directly affected by the level of unemployment in the economy or by the employed/unemployed-status of the agent. Rather making such an ad-hoc assumption, we let the channel of transmission between unemployment and health operate through time-allocation trade-offs and income effects (as reported by literature).

The contribution of the article is manyfold. The first group of contributions concerns the influence of the environmental policy on labor market equilibrium. Our theoretical model demonstrates that a tighter environmental tax (on final output or physical capital) affects labor market equilibrium through different channels: *i)* by

[6] We also investigate the role played by abatement expenditures to mitigate pollution.

rising the tightness in the labor market, *ii)* by reducing the transmission of labor productivity gains towards wage, *iii)* by reducing the incentives to search for a job and *iv)* by increasing the cost payed by a firm when it posts a vacancy job. As a result, a tighter environmental tax increases the steady-state unemployment rate, whatever the source of pollution (physical capital or final output). Furthermore, with respect to the perfect labor market economy, taking into account frictions on labor market and wage bargain, reduces the steady-state level of output, for a given environmental tax and reinforces the negative impact of a tighter environmental tax on final output. Finally, investigating the rise of abatement expenditures as a way of tightening environmental protection, we demonstrate that it does not introduce additional negative impacts arising from the labor market, because orienting a greater part of the revenue of the environmental tax towards abatement entails less distortions that rising tax on physical capital or output. Nevertheless, few resources are available for healthcare and the global effect on the health dividend is not as high as expected by the neutral impact on labor market.

The second group of contributions concerns more specifically the role played by labor market frictions on the health dividend of the environmental policy. First, besides the "conventional effects of the environmental tax (the " direct "pollution reduction" effect, positive for health, and the indirect "crowding-out" effect, negative for health), taking into account frictions on labor market and wage bargain introduces two "new" channels of transmission of the environmental policy to health, through the incentives to search for a job and through the cost of a vacant job. They lead to a reduction in health expenditures, *ceteris paribus* and therefore, with respect to the perfect labor market economy, they reduce the steady-state health status, for a given environmental tax. Second, computing numerical exercises in order to give some informations about the magnitude of the new effects, we find that, according to our chosen parameter values, the existence of frictions on market labor reduces the health dividend of the environmental policy and its positive impact of final output, whatever the policy. The main mechanism relies on the increase in unemployment, leading to a greater decrease in health expenditures. Furthermore, we highlight the role played by the "size" of pollution externality on health showing that such an externality creates a sort of "rebound effect" of the environmental policy. As a result, the greater the pollution externality on health the less efficient is the environmental policy in terms of pollution reduction. This result is explained by the fact that the improvements in health due to the environmental policy rise the efficiency of labor, free resources from healthcare expenditures, and therefore increase output and consumption. As a result pollution rebounds. We also find that in economies where there is a great (respectively small) room for health improvement due to a given reduction of pollution, more frictions on labor market tend to increase (resp. to reduce) the health dividend of the environmental policy, whatever this policy. It means that in economies which experiment great negative externality of pollution on health and suffer from great frictions on labor market, like China, it is expected that pollution reduction generates a higher health dividend. Finally, the robustness analysis of our numerical exercises enable us to highlight how the efficiency of the resources used in the health sector influences the output of the environmental policy in the presence of frictions on labor market and wage bargaining. According to our chosen set of parameter values, in the presence of quite constant returns to scale in healthcare activities, when frictions on labor market and wage bargain are taken into account, the effect of a tighter environmental tax on health becomes negative and sizable, while it is positive and small with perfect labor market. Indeed, the crowding-out of health expenditures due to the positive effect of pollution reduction on health, finally leads to a great diminishing in health status because of the higher returns to scale in the health sector (with respect to our benchmark case). This greater reduction exceeds the positive health effect from the pollution externality of health leading to a global negative impact on health status.

A last contribution of this article concerns the impact of labor market policies on pollution and health improvements. To our knowledge, it is the first time that this impact is investigated in the presence of pollution externality on health. According to our chosen parameter values, labor market policies aimed at reducing unemployment have sizable impacts on pollution reduction and health improvements. In particular, the sign of these impacts (positive or negative) depends on *i)* the nature of the policy, *ii)* the size and the shape of the pollution externality on health and *iii)* the returns to scale in healthcare activities. In our benchmark case, the most efficient labor market policy in terms of unemployment rate reduction consists in lowering the rate of subsidy to unemployment. It generates few gains in terms of pollution reduction while it reduces health-status, but it is the most beneficial policy in terms of pollution and health, compared to reducing the rate of tax on income or increasing the rate of subsidy to vacant job.

The paper is organized as follows. In section two, we present the model. In section three, we describe the steady-state and we study the impact of environmental policy on unemployment and health. In section four, we investigate the impact of abatement expenditures on health. In section five, we examine the case where final output is the source of pollution rather than physical capital. In section six, we compute numerical examples and section seven concludes.

2 The model

The basic framework relies on the search model of unemployment by Shi and Wen (1999) in which we introduce pollution and endogenous health.

2.1 Households

The economy is populated by many identical households whose size is normalized to one. Population size is also normalized to unity. Each household is made of a size one continuum of infinitely-lived agents who are endowed with one unit of time. At any moment an agent has the choice between work, job-search or leisure. Each agent who is searching for a job is considered as unemployed. He is randomly matched with job vacancies. Following Shi and Wen (1999), to solve the aggregation problem linked to the idiosyncratic risks faced by each unemployed agent in the job-matching process, we assume that all agents of a given household care only about the household's utility.[7] As a result, solving the representative household's maximization problem gives the agents' decisions.

The expected lifetime utility of the representative household is:

$$\Lambda(t) \equiv \int_t^{\infty} e^{-\rho(z-t)} u\left(C(z), l(z), h(z)\right) dz \tag{1}$$

Parameter $\rho > 0$ is the subjective discount rate, h denotes health-status, C is consumption and l is the time used for leisure activities defined as:[8]

$$l = 1 - U - L_s$$

where U is the household's hours used in search (unemployment), L_s is the hours supplied by the household in work.

We assume that utility function $u(\cdot)$ is additively separable between consumption and leisure (following Andolfatto, 1996; Merz, 1995; Shi and Wen, 1997, 1999) and we model felicity function between consumption and health as a Cobb-Douglas (following Van Zon and Muysken, 2001):[9]

$$u\left(C, 1 - U - L, h\right) \equiv \log\left(C^{1-\mu_h} h^{\mu_h}\right) - \chi \frac{(U + L)^{1+\varphi}}{1+\varphi}$$

with $\mu_h \in]0, 1[$ the weight of health in utility, $\chi > 0$ the disutility of work and $1/\varphi > 0$ the Frisch elasticity of labor supply.

At each moment of time, some members of the household who are unemployed find a job, and another who are employed lose it, because an idiosyncratic choc destroys a constant part of existing work contracts on market labor. Let denote by m, the rate at which an unemployed agent finds a job. Then mU is the flow of job matches for a household with U unemployed members. Even if m depends on the aggregate numbers of job vacancies and unemployed agents (see below), individuals take m as given. Let denote by $\sigma > 0$ the exogenous constant rate of job destruction. Then, a household's labor supply evolves according to the law:

$$\dot{L_s} = mU - \sigma L_s \tag{2}$$

where $\dot{L_s}$ is the derivative of L_s with respect to time.

Following Grossman (1972) and the subsequent contribution by Cropper (1981), individual's health status evolves over time according to two opposite forces. The first one, positive, relies on health investment made by people in health-enhancing activities, modeled as health expenditures H.[10] The second one, negative, is due

[7] See Shi and Wen (1999, p 460) for more details.

[8] Time index is dropped when there is no confusion

[9] Conversely to Van Zon and Muysken (2001) who used the general form $\frac{\left(C^{1-\mu_h} h^{\mu_h}\right)^{1-1/\sigma_h} - 1}{1-1/\sigma_h}$ where $1/\sigma_h$ is the intertemporal elasticity of substitution and $0 < \sigma_h < 1$, here we choose the logarithmic form ($\sigma_h = 1$) for tractability.

[10] In the appendix A page 32, we develop a general version of this model with time-consuming activities aimed at enhancing health. The qualitative results are not modified but algebraic expressions are more complicated.

to health depreciation which is increased by the ambient air pollution an individual inhales.Therefore, health status evolves according to the law:

$$\dot{h} = \eta H^{\psi} - \delta_h(P)h \tag{3}$$

where $\eta > 0$ is a scale parameter, $\psi \in]0, 1[$ captures the decreasing returns in medical activities, P is pollution and $\delta_h'(P) > 0$.

Budget constraint of the households is given by:

$$\dot{K}_s = (1 - \tau_k)rK_s + \mathit{\Pi} + (1 - \tau_w)\tilde{w}L_s - C - H + S \tag{4}$$

where K is aggregate physical capital, $(1 - \tau_k)r$ is the after-tax interest rate, $\mathit{\Pi}$ is the profit of the firm, τ_w is labor income tax, $\tilde{w}$ is the wage rate w expressed in efficiency terms.[11] For simplicity we abstract from unemployment benefits.[12] S is a lump-sum transfer from the government. Here, pollution arises from physical capital therefore τ_k is also the environmental tax.

A representative household solve the following problem:

$$\begin{aligned}
&\max_{C,h,L_s,U,H,K_s} \int_t^{\infty} e^{-\rho(z-t)} \left\{ \log\left(C^{1-\mu_h} h^{\mu_h}\right) - \chi \frac{(U+L)^{1+\varphi}}{1+\varphi} \right\} dz \\
&s.t. \\
&\dot{K}_s = (1 - \tau_k)rK_s + \mathit{\Pi} + (1 - \tau_w)\tilde{w}L_s - C - H + S \\
&\dot{L}_s = mU - \sigma L_s \\
&\dot{h} = \eta H^{\psi} - \delta_h(P)h \\
&K_s(0) = K_{s0},\ L_s(0) = L_{s0},\ h(0) = h_0 \ given
\end{aligned}$$

First-order conditions yield:

$$\dot{C} = C\left[(1 - \tau_k)r - \rho\right]$$

$$\chi\,(U + L)^{\varphi} = m\lambda_L, \tag{5}$$

$$\lambda_L = \frac{(1 - \tau_w)\tilde{w}(1 - \mu_h)/C - \chi\,(U + L)^{\varphi} + \dot{\lambda}_L}{\rho + \sigma}, \tag{6}$$

$$\frac{1 - \mu_h}{C} = \lambda_h \eta \psi H^{\psi - 1} \tag{7}$$

$$\lambda_h = \frac{\mu_h/h + \dot{\lambda}_h}{\rho + \delta_h(P)} \tag{8}$$

The first condition is the standard Euler equation. Condition (5) means that the opportunity cost of search (the left-hand side) is equal to the marginal benefit of search (the right-hand side). Condition (6) states that the capital value of the employment to the household (the left-hand side) is equal to the present value of the cash flow generated by the employment $(1 - \tau_w)\tilde{w}u_1 - u_2$ plus capital gains $\dot{\lambda}_L$,

[11] All variables with a ˜ are expressed in efficiency terms: $\tilde{x} = h \times x$.

[12] In the general model, we assume that unemployment benefits are defined as $\tau_u \tilde{w} U$ where τ_u is the rate of subsidy to unemployment. Qualitative results are not modified.

discounted by $\rho + \sigma$. Condition (7) means that the opportunity cost of improving health (the left-hand side) is equal to the marginal gains from improving health (the right-hand side). Condition (8) states that the capital value of health (the left-hand side) is equal to the present value of the utility gains from improving health (μ_h/h) plus capital gains $\dot{\lambda}_h$, discounted by $\rho + \delta_h(P)$.

2.2 The firms

Final output Y is produced by firms operating under perfect competition, with a constant-returns to scale Cobb-Douglas production function:

$$Y = \mathcal{F}(K_d, hL_d) \equiv Z{K_d}^{\alpha}\left(hL_d\right)^{1-\alpha} \qquad \text{with} \qquad \alpha \in]0,1[\tag{9}$$

where K_d is the demand for aggregate physical capital and L_d is the demand for labor. In order to ease the presentation of the model, we assume that aggregate physical capital does not depreciate.[13] $Z > 0$ is a productivity parameter. h captures worker productivity which is assumed to depend on health exclusively.[14] Because of frictions on market labor, the firm faces a linear cost of adjustment of the stock of labor, such that the demand for labor evolves according to the law:

$$\dot{L_d} = qV - \sigma L_d$$

where q is the instantaneous probability to fill vacant job.

An individual firm solve the following problem:

$$\max_{K_d, L_d, V} \int_t^{\infty} \mathit{\Pi} e^{(1-\tau_k)r(t-z)} dz$$
$$s.t.$$
$$\mathit{\Pi} = Y - \tilde{w}L_d - rK_d - (1-\tau_v)\tilde{\xi}_V V$$
$$\dot{L_d} = qV - \sigma L_d$$
$$Y = \mathcal{F}\left(K_d, hL_d,\right)$$
$$K_d(0) = K_{d0},\ L_d(0) = L_{d0}\ given$$

where $\tilde{\xi}_V$ is the flow cost per vacancy (ξ_V) in efficiency terms and τ_v is the per unit subvention to job posting.

First-order conditions are

$$\mathcal{F}_K = r, \tag{10}$$
$$\mu_L q = (1-\tau_v)\tilde{\xi}_V, \tag{11}$$
$$\mu_L = \frac{\mathcal{F}_L - \tilde{w} + \dot{\mu}_L}{(1-\tau_k)r + \sigma}, \tag{12}$$

Condition (10) means that physical capital is paid at its marginal contribution. According to (11), the effective marginal cost of vacancy $\tilde{\xi}_V$ equals the marginal benefit of vacancy to the firm $\mu_L q$. Condition (12) states that the capital value of vacancy to the firm (the left-hand side) is equal the present value of the clash flow linked to vacancy $(1-\tau_y)\mathcal{F}_L - \tilde{w}$ plus capital gains $\dot{\mu}_L$, discounted by $(1-\tau_k)r + \sigma$.

[13] In the general version of the model (Appendix A page 32), we relax this assumption. Qualitative results are not modified.

[14] See Mathieu-Bolh and Pautrel (2016) for a justification.

2.3 Matching and wage determination

On labor market, there is a matching process through which vacant jobs and employed individuals are randomly matched with each other (Pissarides, 1990). Nevertheless, the aggregate flow of job matches are deterministic and given by a matching function denoted by $M(U,V)$ where U and V are respectively the unemployed agents and aggregate job vacancies. We assume, as conventional, that the function $M(\cdot,\cdot)$ is a linearly homogenous function:

$$M(U,V) = M_0 V^j U^{1-j}, \qquad M_0 > 0$$

where $j \in (0,1)$ is the elasticity of vacancy in job matches. We denote $\theta \equiv V/U$ as the tightness of labor market: a smaller θ represents a tighter market. Defining the matches per employed by m and the matches per vacancy by q, with the constant-returns-to-scale technology of the matching function, both matches depend only on θ:

$$m = m(\theta) = M_0\theta^j \qquad \text{and} \qquad q = q(\theta) = m(\theta)/\theta \tag{13}$$

Once an unemployed agent is matched with a vacant post, the agent and the firm decide the agent's current and future wages. As usual, the wage is defined through a negotiation aimed at maximizing the weighted Nash product of the agent's and the firm's surpluses. An additional member working dL at the wage $\tilde{w}$ increases the household's utility by $\left[(1-\tau_w)\tilde{w}\frac{(1-\mu_h)}{C} - \chi(U+L)^{\varphi}\right] dL$. An additional worker dL at the wage $\tilde{w}$ increases the firm's current-valued surplus by $[\mathcal{F}_L - \tilde{w}]\, dL$. As a result, the negotiation consists in the following program:

$$\max_{\tilde{w}} \left[\mathcal{F}_L - \tilde{w}\right]^{1-\phi} \left[(1-\tau_w)\tilde{w}\frac{(1-\mu_h)}{C} - \chi(U+L)^{\varphi}\right]^{\phi}$$

where $\phi \in (0,1)$ is the worker's bargaining power. Solving the Nash problem yields:

$$\tilde{w} = \phi\mathcal{F}_L + (1-\phi)\frac{\chi(U+L)^{\varphi}C}{(1-\tau_w)(1-\mu_h)} \tag{14}$$

2.4 Government and ecology

Ecology is captured by the flow of pollution emissions arising from aggregate physical capital and there is no abatement activities.[15] As a result, we define pollution as:

$$P = \pi_k K \tag{15}$$

where $\pi_k \in [0,1]$ is the polluting capacity of the physical capital stock.

The government budget is balanced at all times. The environmental tax revenue is used with the labor tax revenue to fund vacancy subsidies and lump-sum transfers:

$$\tau_k r K + \tau_w \tilde{w} L = S + \tau_v \tilde{\xi}_V V \tag{16}$$

[15] See Appendix A page 32 where pollution stock and abatement activities are introduced, with the aggregate output as an alternative source of pollution.

3 Environmental policy, unemployment and health

In this section we investigate how the imperfections on labor market modify the impact of the environmental policy on both the economic activity and health, at the steady-state equilibrium. The steady-state equilibrium is such that C, H, U, L, V, K, Y are constant.

The resolution of the model yields the following dynamic system of seven variables, with four forward-looking variables C, H, U and θ and three predetermined variables K, h and L:[16]

$$\dot{C} = \left[(1-\tau_k)\alpha Z\left(\frac{K}{hL}\right)^{\alpha-1} - \rho\right] C \tag{17}$$

$$\dot{H} = \frac{H}{1-\psi}\left\{(1-\tau_k)\alpha Z\left(\frac{K}{hL}\right)^{\alpha-1} + \delta_h(P) - \left(\frac{C}{h}\right)\frac{\mu_h}{1-\mu_h}\eta\psi H^{\psi-1}\right\} \tag{18}$$

$$\dot{\theta} = \frac{\theta}{1-j}\left\{\sigma + (1-\tau_k)\alpha Z\left(\frac{K}{hL}\right)^{\alpha-1} - \frac{(\mathcal{F}_L - \tilde{w})\, m(\theta)/\theta}{(1-\tau_v)\tilde{\xi}_V} - \frac{\dot{h}}{h}\right\} \tag{19}$$

$$\dot{h} = \eta H^{\psi} - \delta_h(P)h \tag{20}$$

$$\dot{L} = m(\theta)U - \sigma L \tag{21}$$

$$\dot{K} = Z\left(\frac{K}{hL}\right)^{\alpha} hL - C - H - h\xi_V\theta U \tag{22}$$

$$\dot{U} = \varphi^{-1}(U+L)\left\{m(\theta) + \sigma + \rho - \frac{(1-\tau_w)(1-\mu_h)}{C\chi(U+L)^{\varphi}}m(\theta)\tilde{w} + j\frac{\dot{\theta}}{\theta} - \varphi\frac{\dot{L}}{U+L}\right\} \tag{23}$$

with $\tilde{w} = \phi\mathcal{F}_L + (1-\phi)\frac{C\chi(U+L)^{\varphi}}{(1-\tau_w)(1-\mu_h)}$ and $P = \pi_k K$ from (15).

At the steady-state equilibrium, $\dot{U} = 0$, then from (23) and the expression of $\tilde{w}$ we obtain:

$$\tilde{w}^{\star} = \Phi(\theta^{\star})\mathcal{F}_L^{\star} \qquad \text{where} \quad \Phi(\theta^{\star}) \equiv \frac{\phi(\rho+\sigma+m(\theta^{\star}))}{\rho+\sigma+m(\theta^{\star})\phi} < 1 \tag{24}$$

and $\Phi'(\theta^{\star}) > 0$. $\Phi(\theta^{\star})$ captures the first impact of unemployment on our economy, through the wage bargaining process. Because $\phi < 1$, $\Phi(\theta^{\star})$ is increasing in matching probability. The lower matching probability is, the smaller is bargained wage with respect to labor productivity. As a result, a tighter labor market reduces the transmission of an increase in labor productivity to wage. And this phenomenon is stronger for low level of worker's bargaining power (ϕ).

At the steady-state equilibrium, $\dot{C} = 0$, then it comes from (17), $(1-\tau_k)\alpha Z\left(\frac{K}{hL}\right)^{\alpha-1} = \rho$, and we obtain the steady-state physical capital per efficient unit of labor, $k \equiv K/(hL)$, as a function of the environmental tax:

$$k^{\star} = f(\tau_k) \qquad \text{where} \qquad f(\tau_k) \equiv \left[\frac{\alpha(1-\tau_k)Z}{\rho}\right]^{1/(1-\alpha)} \tag{25}$$

[16] The study of the dynamics is out of the scope of this paper and here we limit our analysis to the steady-state.

At the steady-state equilibrium, $\dot{H} = 0$ and $\dot{h} = 0$, then from equations (18) and (20), the steady-state expenditures in health care can be expressed with respect to $C^\star$:

$$H^\star = \mathcal{E}(P^\star)\ C^\star \qquad \text{with } \mathcal{E}(P^\star) \equiv \frac{\psi\delta_h(P^\star)}{\rho + \delta_h(P^\star)}\left(\frac{\mu_h}{1-\mu_h}\right) \tag{26}$$

where $\delta_h'(P^\star) > 0$ and $d\mathcal{E}(P^\star)/dP^\star > 0$.

At the steady-state equilibrium, $\dot{\theta} = 0$, then from (19) and (9), the tightness of labor market at the steady-state $\theta^\star$ is given by:

$$(1-\alpha)Zf(\tau_k)^\alpha = \frac{\theta^\star\,(\rho+\sigma)\,(1-\tau_v)\xi_V}{m(\theta^\star)\,[1-\Phi(\theta^\star)]} \tag{27}$$

and because $\dot{L} = 0$, from (2) it comes

$$U^\star = \frac{\sigma}{m(\theta^\star)} L^\star \tag{28}$$

Then:

Proposition 1. *In the presence of frictions of labor market and wage bargaining, a tighter environmental tax*

1. *increases the tightness in labor market at steady-state:*

$$\theta^\star = \Theta(\tau_k) \qquad \textit{with} \qquad \Theta'(\tau_k) < 0$$

2. *rises the steady-state unemployment rate $U^\star / (U^\star + L^\star)$.*

Proof. Point 1 is straightforward from equation (27). Point 2 is derived from equation (28) and Proposition 1.1. □

The influence of the environmental tax on labor market tightness can be explained as follows. When the environmental tax increases, ceteris paribus, the marginal benefit of vacancy diminishes due the crowding-out effect of the tax which reduces labor reward. Because the marginal cost of vacancy ξ_V remains constant, the firm posts less vacant jobs. As a result, $\theta = V/U$ diminishes. Because unemployment is directly linked to labor market tightness, a higher environmental tax rises unemployment rate in the economy. This result confirms the one found by Hafstead and Williams III (2018) in a different setting.

From (23), (24) and (28), we can re-express the equality between the opportunity cost of search and the marginal benefit of search, obtaining a relationship between $C^\star/h^\star$ and $L^\star$:

$$\frac{C^\star}{h^\star} = (1-\alpha)Zf(\tau_k)^\alpha \left(\frac{1-\mu_h}{\chi}\right) \mathit{\Lambda}_1(\theta^\star)\, L^{\star-\varphi}$$

$$\text{where } \mathit{\Lambda}_1(\theta^\star) \equiv \Phi(\theta^\star)\frac{(1-\tau_w)m(\theta^\star)}{\sigma+\rho+m(\theta^\star)}\left(\frac{\sigma}{m(\theta^\star)}+1\right)^{-\varphi} \tag{29}$$

with $0 < \Lambda_1(\theta^\star) < 1$ and $d\Lambda_1(\theta^\star)/d\tau_k < 0$.

Because $\dot{K} = 0$, using (22), (16), (28) and (4), we obtain a second relationship between $C^\star/h^\star$ and $L^\star$:

$$\frac{C^\star}{h^\star} = \frac{Zf(\tau_k)^\alpha - \Lambda_2(\theta^\star)}{1+\mathcal{E}(P^\star)} L^\star \qquad \text{where } \Lambda_2(\theta^\star) \equiv \frac{\sigma\theta^\star}{m(\theta^\star)}\xi_V \tag{30}$$

with $\Lambda_2(\theta^\star) > 0$ and $d\Lambda_2(\theta^\star)/d\tau_k < 0$.

In equation (29), $\Lambda_1(\theta^\star)$ captures three elements introduced by the existence of unemployment which directly impact the incentive to search. First, because of wage bargaining, wage rate is partially delinked from labor productivity, proportionally through the coefficient $\Phi(\theta^\star)$. A rising environmental tax increases this disconnection between wage and labor productivity, and therefore reduces incentives to search for a job. Second, everything being the same, to obtain a job, it is required to match with a vacancy job (with a given probability m) and when you get a job you have a probability σ to lose it. Therefore, a rising environmental tax diminishes the probability of matching and, as consequence, the incentives to search. This is captured by the term $\frac{(1-\tau_w)m(\theta^\star)}{\sigma+\rho+m(\theta^\star)}$. Third, unemployment reduces non-leisure time forcing unemployed to search for a new job. As a result, the household labor force supply is reduced by this amount. This is captured by the term $\left(\frac{\sigma}{m(\theta^\star)}+1\right)^{-\varphi}$.

Equation (30) is derived from the equality between household's incomes and household's expenditures. Because the household earns firms, they get their profits which are negatively influenced by the cost of posting vacant jobs, itself negatively impacted by the probability of matching. This effect, representing the "*economy's cost of vacancy*" is captured by $\Lambda_2(\theta^\star)$. Everything being equal, it reduces the amount consumed by the household, with respect to the case of a perfect market labor. Rising environmental tax diminishes $\Lambda_2(\theta^\star)$ and therefore increases the economy's cost of vacancy because the probability of filling the vacant post reduces.

As a result, the presence of frictions in labor market introduces new channels of transmission of the environmental tax to the economy.

Proposition 2. *In the presence of frictions on labor market and wage bargaining, a tighter environmental tax*

1. *reduces the transmission of labor productivity gains to wage: $\Phi(\theta^\star)$ with $d\Phi(\theta^\star)/d\tau_k < 0$;*
2. *reduces the incentives to search for a job. This effect is captured through the term $\Lambda_1(\theta^\star)$: a rise in $\Lambda_1(\theta^\star)$ means a higher incentives to search for a job;*
3. *increases the "economy's cost of vacancy". This effect is captured through the term $\Lambda_2(\theta^\star)$: a decrease in $\Lambda_2(\theta^\star)$ means a higher "economy's cost of vacancy".*

Proof. Point 1 is derived from equation (24). Point 2 is derived from the expression of $\Lambda_1(\theta^\star)$ in equation (29) and Proposition 1.1. Point 3 is straightforward from the expression of $\Lambda_2(\theta^\star)$ in equation (30) and Proposition 1.1. □

Finally,[17] using (29), (30) and previous results, we obtain the steady-state value of key variables as a function of pollution and the environmental tax. The amount of labor employed in production at the steady-state is :

$$L^\star = \mathcal{L}(P^\star, \tau_k) \equiv \left[\frac{(1+\mathcal{E}(P^\star))(1-\alpha) Z \left(\frac{1-\mu_h}{\chi}\right) \mathit{\Lambda}_1\left(\mathit{\Theta}(\tau_k)\right)}{Z - \frac{\mathit{\Lambda}_2(\mathit{\Theta}(\tau_k))}{f(\tau_k)^\alpha}} \right]^{\frac{1}{1+\varphi}}, \tag{31}$$

The steay-state level of consumption is:

$$C^\star = \left[\frac{\eta \mathcal{E}(P^\star)^{\psi+\iota}}{\delta_h(P^\star)}\right]^{\frac{1}{1+\varphi}} \left\{ \left[1+\mathcal{E}(P^\star)\right]^{-\varphi} (1-\alpha) Z f(\tau_k)^\alpha \left(\frac{1-\mu_h}{\chi}\right) \mathit{\Lambda}_1\left(\mathit{\Theta}(\tau_k)\right) \right.$$
$$\left. \times \left[Z f(\tau_k)^\alpha - \mathit{\Lambda}_2\left(\mathit{\Theta}(\tau_k)\right)\right]^\varphi \right\}^{\frac{1}{(1-\psi)(1+\varphi)}} \tag{32}$$

The steady-state final output is:

$$Y^\star = \mathcal{Y}(P^\star, \tau_k) \equiv Z f(\tau_k)^\alpha \left\{ \left[\frac{\eta \mathcal{E}(P^\star)^\psi}{\delta_h(P^\star)}\right]^{1+\varphi} \left[1+\mathcal{E}(P^\star)\right]^{1-\psi(1+\varphi)} \right. \tag{33}$$
$$\left. \times \left[(1-\alpha) Z f(\tau_k)^\alpha \left(\frac{1-\mu_h}{\chi}\right) \mathit{\Lambda}_1\left(\mathit{\Theta}(\tau_k)\right)\right] \left[Z f(\tau_k)^\alpha - \mathit{\Lambda}_2\left(\mathit{\Theta}(\tau_k)\right)\right]^{\psi(1+\varphi)-1} \right\}^{\frac{1}{(1-\psi)(1+\varphi)}}$$

where $\mathit{\Theta}'(\tau_k) < 0$, $\mathit{\Lambda}_1\left(\mathit{\Theta}(\tau_k)\right)$ and $\mathit{\Lambda}_2\left(\mathit{\Theta}(\tau_k)\right)$ are respectively defined in equation (29) and (30). Using (15) and (33), the steady-state flow of pollution is given by the following implicit function:

$$P^\star = \pi_k f(\tau_k)^{1-\alpha} \mathcal{Y}(P^\star, \tau_k)/Z \tag{34}$$

As demonstrated in Appendix B page 38, the net flow of pollution at steady-state can be written as:

$$P^\star = \mathcal{P}(\tau_k) \qquad \text{with} \qquad \mathcal{P}'(\tau_k) < 0 \tag{35}$$

From previous results, it comes

Proposition 3. *With respect to the perfect labor market economy, when frictions on labor market and wage bargain are taken into account:*

1. *the "incentives to search a job" effect (captured by $\mathit{\Lambda}_1\left(\mathit{\Theta}(\tau_k)\right)$) reduces the steady-state level of output for a given environmental tax, and reinforces the crowding-out effect of a tighter environmental tax on final output;*
2. *the "economy's cost of vacancy" effect (captured by $\mathit{\Lambda}_2\left(\mathit{\Theta}(\tau_k)\right)$) reduces the steady-state level of output for a given environmental tax, and reduces the crowding-out effect of a tighter environmental tax on final output when $\psi > 1/(1+\varphi)$.*

Proof. Straightforward from (33) and (35). □

[17] Demonstration in appendix A page 35.

Proposition 3 states that the new channels of transmission of the environmental tax highlighted in Proposition 2 introduce two opposite forces when $\psi > 1/(1+\varphi)$, because frictions on labor market, through $\Lambda_2\left(\Theta(\tau_k)\right)$, diminishes the steady-state level of health while it rises the number of worked hours. Because the case $\psi > 1/(1+\varphi)$ is the most realistic (see calibration in section 6), it is not possible to conclude on the positive or negative impact of a tighter environmental tax on the crowding-out effect due to labor market frictions. We will investigate this question using numerical simulations in section 6.

Finally, from previous results, we can express the steady-state health-status of each individual as:

$$h^{\star} = \mathcal{H}(\tau_k) \equiv \left\{ \frac{\eta \mathcal{E}\left(\mathcal{P}(\tau_k)\right)^{\psi}}{\delta_h(\mathcal{P}(\tau_k))} \left(1 + \mathcal{E}\left(\mathcal{P}(\tau_k)\right)\right)^{\frac{-\psi\varphi}{1+\varphi}} \left\{\Lambda_1\left(\Theta(\tau_k)\right)\left[Zf(\tau_k)^{\alpha} - \Lambda_2\left(\Theta(\tau_k)\right)\right]^{\varphi}\right\}^{\frac{\psi}{1+\varphi}} \right\}^{\frac{1}{1-\psi}}, \tag{36}$$

Proposition 4. *With respect to the perfect labor market economy, when frictions on labor market and wage bargain are taken into account:*

1. *the steady-state health status is reduced, for a given environmental tax,*
2. *the "incentives to search a job" effect (captured by $\Lambda_1\left(\Theta(\tau_k)\right)$) introduces an additional negative impact of a tighter environmental tax on steady-state health status.;*
3. *the "economy's cost of vacancy" effect (captured by $\Lambda_2\left(\Theta(\tau_k)\right)$) introduces an additional positive impact of a tighter environmental tax on steady-state health status.*

Proof. From equation (36) and Propositions 2.2 and 2.3. □

Proposition 4.1 states that, not taking into account imperfections on labor market leads to overestimate the steady-state level of health-status in the economy. Indeed, through $\Lambda_1\left(\Theta(\tau_k)\right) \in [0,1]$, labor market imperfections reduce the amount of hours worked and therefore the labor income generated in the economy. As a result, the resources invested in health improvements decrease. Furthermore, through $\Lambda_2\left(\Theta(\tau_k)\right) > 0$, labor market imperfections reduce the profits of the firms accruing to households because of the cost of posting jobs. As a results, agents decrease their expenditures, especially in health.

The impact of labor market imperfections on the "health-dividend" of the environmental tax is less clear. Indeed, there are here four channels through which environmental tax impacts health-status. First, by reducing pollution, the environmental tax reduces its detrimental on health, and *ceteris paribus* the individual health status rises. This effect, called the "*pollution externality on health*" effect is captured by the term $\left(\frac{\eta\mathcal{E}(P^{\star})^{\psi}}{\delta_h(P^{\star})}\right)^{\frac{1}{1-\psi}} \left(1+\mathcal{E}(P^{\star})\right)^{\frac{-\psi\varphi}{(1-\psi)(1+\varphi)}}$ in equation (36). It relies on the positive effect of the environmental tax on health due to the reduction of pollution, through both the reduction of the rate of health depreciation and the decrease in health expenditures. Second, the environmental tax has a crowding out effect on production which leads to a decrease in output and income. As a result, *ceteris* *paribus* health expenditures reduce and therefore health status diminishes. This negative impact on health, called the "*crowding out*" effect is captured by the term $Zf(\tau_k)^\alpha$ in equation (36). Third, the increase in environmental tax rises the tightness on market labor and the unemployment rate. As noted in Proposition 2 page 13, this directly reduces incentives for agent to search for a job because labor productivity improvements translated less in an increase in income (through $\Phi(\theta^\star)$), the probability to match $m(\theta^\star)$ is lowered and the increase in unemployment reduces leisure-time. This negative effect on health, called the "*incentives to search for a job*" effect is captured by the term $\Lambda_1\left(\Theta(\tau_k)\right)$ in equation (36). Fourth, as noted in Proposition 3, by reducing the probability of matching, a tighter environmental tax rises the cost of vacancy and then the profits of the firms owned by agents. As a result, the amount of resources agents are able to use in order to improve health is reduced. This negative effect on health, called the "*vacancy cost*" effect is captured by the term $\Lambda_2\left(\Theta(\tau_k)\right)$ in equation (36). The two first channels are "conventional" channels already highlighted in the literature, while the two last channels are "new" and related to the introduction of labor market imperfections.

Nevertheless, the global impact of these two new channels is not clear-cut. On one hand by reducing $\Lambda_1\left(\Theta(\tau_k)\right)$ a higher tax reduces steady-state health status, but on other hand, by reducing $\Lambda_2\left(\Theta(\tau_k)\right)$, it reduces the crowding-out effect. As highlighted by the expressions of $\Lambda_1\left(\Theta(\tau_k)\right)$ in equation (29), $\Lambda_2\left(\Theta(\tau_k)\right)$ in equation (30) and the implicit expression of $\Theta(\tau_k)$ given by equation (27), several variables interact to determine the sign of the net impact. Further investigations are required to evaluate this net impact and to determine how these two effects modify the health dividend found in the presence of prefect market labor. We will examine this point in section 6 using numerical simulations.

4 Abatement expenditures as an alternative environmental policy

Many empirical studies, especially on environment and labor uses abatement expenditures as a proxy for the environmental policy strength. To investigate the role played by abatement expenditures on the health-dividend of environmental policy, we modify our model (equations 15 and 16) as follows. We consider now that P is the net flow of pollution defined as the difference between pollution emissions $\pi_k K$ and the reduction of pollution arising from abatement activities. Abatement activities, denoted by A, use forgone output and are funded by a part $\beta \in [0,1]$ of the environmental tax revenues, such as:

$$A = \beta\tau_k K \tag{37}$$

Thus, P is now the stock of pollution and equation (15) is replaced by the low of motion of the stock de pollution :

$$\dot{P} = \pi_k K - \beta\tau_k K - \gamma P \tag{38}$$

where $\gamma > 0$ is the regeneration rate of nature.

The remaining of the environmental tax revenue is used with the labor tax revenue to fund vacancy subsidies and lump-sum transfers, then (16) becomes:

$$(1-\beta)\tau_k rK + \tau_w \tilde{w} L = S + \tau_v \tilde{\xi}_V V \tag{39}$$

Replacing respectively (15) by (38) and (16) by (39) in the model, we derive the following proposition:

Proposition 5.

1. *The part of environmental tax revenue funding abatement (β) does not affect the tightness on labor market and the unemployment rate.*

2. *A greater part of environmental tax revenue dedicated to abatement (a higher β) reduces the steady-state stock of pollution, rises the steady-state health-status and has an incertain impact on the steady-state level of output.*

Proof. From equations (A.36), (A.37) in Appendix A and (35). □

This proposition means that, in the presence of labor market frictions and wage bargaining, increasing the part of environmental tax revenue funding abatement (β) as a way of tightening environmental protection would be better for health than rising the environmental tax, because it does not introduce additional negative impacts arising from the labor market. This implication is quite intuitive and relies on the fact that using abatement expenditures for tightening environmental policy entails less distortions than rising tax on capital or output. As a result, pollution decreases more because of more abatement activities and it benefits to health through the pollution externality effect. We will investigate this point with numerical simulations in section 6.

5 Output as the source of pollution

In previous sections, we assumed that the source of pollution is physical capital and therefore the environmental policy taxes physical capital. Nevertheless, final output is also frequently viewed in the literature as an alternative source of pollution. Do our results remain valid when the source of pollution is final output rather than physical capital and therefore the environmental policy consists in taxing final output rather than physical capital income?

When output is the only source of pollution, the general model is "modified" in the following ways.[18] First, the tax on capital income, τ_k is assumed to be null. Rather, we assume that final output is taxed at $\tau_y \in]0,1[$, which represents the environmental tax, now.

Therefore (25) becomes

$$k^\star = \mathcal{B}_1 g(\tau_y) \tag{25y}$$

where $\mathcal{B}_1 \equiv \left[\frac{Z\alpha}{\rho}\right]^{1/(1-\alpha)}$ and $g(\tau_y) = (1-\tau_y)^{1/(1-\alpha)}$.

[18]For a demonstration, see the general model in Appendix A page 32.

Emissions arising from $\pi_y Y^\star$, equation (15) becomes

$$P^\star = \pi_y Y^\star \tag{15y}$$

with $\pi_y \in]0,1[$ captures the polluting capacity of final output.

The remaining of the model is mostly unchanged, except that the term $f(\tau_k)^\alpha$ is replaced by ${\mathcal{B}_1}^\alpha g(\tau_y)$, and $\left[Z - \dfrac{\tau_k}{1-\tau_k}\rho f(\tau_k)^{1-\alpha}\right] f(\tau_k)^\alpha$ is replaced by $\left[Z\left(\dfrac{1-\beta\tau_y}{1-\tau_y}\right)\right]{\mathcal{B}_1}^\alpha g(\tau_y)$.

As a result, $\theta^\star$ previously defined by equation (27) is now given by:

$$(1-\alpha)Z{\mathcal{B}_1}^\alpha g(\tau_y) = \frac{\theta^\star(\rho+\sigma)(1-\tau_v)\xi_V}{m(\theta^\star)\left[1-\Phi(\theta^\star)\right]} \tag{27y}$$

When the environmental tax is upon output rather than physical capital, the environmental tax increases the tightness on labor market : $\theta^\star = \Theta^y(\tau_y)$ with $\Theta^{y\prime}(\tau_y) < 0$. As a consequence, the unemployment rate increases with a tightening of the environmental tax.

Furthermore, equation (26) remains the same, then it comes

$$L^\star = \left[\frac{(1-\alpha)Z\left(1+\mathcal{E}(P^\star)\right)(1-\mu_h)\Lambda_1\left(\Theta^y(\tau_y)\right)}{\chi\left[Z\left(\frac{1-\beta\tau_y}{1-\tau_y}\right) - \frac{\Lambda_2(\Theta^y(\tau_y))}{{\mathcal{B}_1}^\alpha g(\tau_y)}\right]}\right]^{\frac{1}{1+\varphi}} \tag{31y}$$

We also obtain:

$$\begin{aligned} C^\star = \left[\frac{\eta\mathcal{E}(P^\star)^{\psi+\iota}}{\delta_h(P^\star)}\right]^{\frac{1}{1+\varphi}} \left[1+\mathcal{E}(P^\star)\right]^{\frac{-\varphi}{(1-\psi)(1+\varphi)}} \Bigg\{ & (1-\alpha)Z{\mathcal{B}_1}^\alpha g(\tau_y)\left(\frac{1-\mu_h}{\chi}\right)\Lambda_1\left(\Theta^y(\tau_y)\right) \\ & \times\left[Z\left(\frac{1-\beta\tau_y}{1-\tau_y}\right){\mathcal{B}_1}^\alpha g(\tau_y) - \Lambda_2\left(\Theta^y(\tau_y)\right)\right]^\varphi\Bigg\}^{\frac{1}{(1-\psi)(1+\varphi)}} \end{aligned} \tag{32y}$$

and

$$\begin{aligned} h^\star = \left[\frac{\eta\mathcal{E}(P^\star)^{\psi+\iota}}{\delta_h(P^\star)}\right]^{\frac{1}{1+\varphi}} \left[1+\mathcal{E}(P^\star)\right]^{\frac{-\varphi\psi}{(1-\psi)(1+\varphi)}} \Bigg\{ & (1-\alpha)Z{\mathcal{B}_1}^\alpha g(\tau_y)\left(\frac{1-\mu_h}{\chi}\right)\Lambda_1\left(\Theta^y(\tau_y)\right) \\ & \times\left[Z\left(\frac{1-\beta\tau_y}{1-\tau_y}\right){\mathcal{B}_1}^\alpha g(\tau_y) - \Lambda_2\left(\Theta^y(\tau_y)\right)\right]^\varphi\Bigg\}^{\frac{\psi}{(1-\psi)(1+\varphi)}} \end{aligned} \tag{36y}$$

and

$$\begin{aligned} Y^\star = \tilde{\mathcal{Y}}(P^\star,\tau_y) \equiv Z\left[g(\tau_y)^{\alpha(1-\psi)+\psi}\frac{\eta\mathcal{E}(P^\star)^\psi}{\delta_h(P^\star)}\right]^{\frac{1}{1-\psi}} & \left[(1-\alpha)Z\left(\frac{1-\mu_h}{\chi}\right)\Lambda_1\left(\Theta^y(\tau_y)\right)\right]^{\frac{1}{(1-\psi)(1+\varphi)}} \\ & \times\left[\frac{\left(1+\mathcal{E}(P^\star)\right)}{Z\left(\frac{1-\beta\tau_y}{1-\tau_y}\right) - \frac{\Lambda_2(\Theta^y(\tau_y))}{{\mathcal{B}_1}^\alpha g(\tau_y)}}\right]^{\frac{1-\psi(1+\varphi)}{(1-\psi)(1+\varphi)}} \end{aligned} \tag{33y}$$

with $\Theta^{y\prime}(\tau_y) < 0$ and finally

$$P^\star = \pi_y\tilde{\mathcal{Y}}(P^\star,\tau_y) \tag{34y}$$

Following the same rationale than in appendix B page 38, it comes that the net flow of pollution at steady-state is defined as:

$$P^\star = \tilde{\mathcal{P}}(\tau_y) \qquad \text{with} \qquad \mathcal{P}'(\tau_y) < 0 \tag{35y}$$

Proposition 6. *The influences of labor market imperfections on the economy are qualitatively similar when the source of pollution is final output than when the source of pollution is physical capital.*

Proof. Straightforward from equations (32y), (36y), (33y) and (35y). □

We will investigate the quantitative impacts of environmental policy for both sources of pollution in the next section.

6 Numerical examples

In this section, we simulate the model in order to give some informations about the magnitude of the new effects highlighted in the previous sections and to investigate how the effects of the environmental policy on health reported by the theoretical literature are modified in the presence of labor market imperfections.

6.1 Calibration

We calibrate a benchmark version of the general model presented in Appendix A, where pollution is modeled as a stock, unemployment benefits are introduced as $\tau_u \tilde{w} U$ with $\tau_u \in [0,1]$, physical capital depreciates at a rate $\delta \in [0,1]$, there are abatement activities, final output is a source of pollution besides physical capital and is taxed at rate $\tau_y \in [0,1]$. The benchmark values of parameters are reported in Table 1.

Labor market parameters: The steady-state values of labor market tightness $\theta^\star$ and the unemployment rate $u^\star$ come from Landais et al. (2018, p.28) based on the Census Population Survey (CPS) data for 1990-2014. Because the average number of vacancies for 1990-2014 is 3.80 million and the average number of unemployed workers in CPS data for 1990-2014 is 8.82 million, we have $\theta^\star = 3.8/8.82 = 0.43$ and the average unemployment rate is $u^\star = 6.1\%$. From the definition of $u = U/(U+L)$ and equation (28) and using the chosen value of σ from Shimer (2005), we obtain that $m(\theta^\star) = \left(\frac{1}{0.061} - 1\right) \times 0.01 = 1.54$. Using (13) it comes $M_0 = 1.98 \approx 2$ and $q(\theta^\star) = 1.54/0.43 = 3.58$ which is quite close to the value reported by Silva and Toledo (2009, p.8). Following the so-called Hosios (1990) condition for efficiency, the bargaining power ϕ is assumed to be equal to $1 - \alpha$. The elasticity of vacancy in job matches j is set to 0.3 according to Petrongolo and Pissarides (2001) and the flow cost per vacancy is set to 0.3, which is consistent with Silva and Toledo (2009).

Values of tax rates τ_u and τ_w are consistent with Gomme and Rupert (2007) and McDaniel (2007) on the period 1990-2014. Per unit subvention to job posting τ_v is arbitrary set to 0.2.

Table 1: Benchmark parameter values

Parameter		Value	Source
Preference and technology			
- Weight of health in utility	μ_h	0.4	French (2005)
- Disutility of work	χ	13	*matches steady-state target*
- Frisch labor supply elasticity	φ	2	Chetty et al. (2011)
- Subjective rate of time preference	ρ	0.04	correspond to a 4% annual pre-tax interest rate
- Share of physical capital in production	α	1/3	De La Croix and Michel (2002)
- Productivity parameter	Z	0.72	*matches steady-state targets*
- Physical capital depreciation rate	δ	0.05	Gomme and Rupert (2007)
Labor market			
- Labor income tax	τ_w	0.2	Gomme and Rupert (2007); McDaniel (2007)
- Rate of subsidy to unemployment	τ_u	0.5	Chetty (2008)
- Effectiveness of matching	M_0	1.98	*matches steady-state targets*
- Elasticity of vacancy in job matches	j	0.3	Petrongolo and Pissarides (2001)
- Workers bargaining power in wage negociation	ϕ	0.7	To verify Hosios (1990) condition
- Flow cost per vacancy	ξ_v	0.3	Silva and Toledo (2009)
- Per unit subvention to job posting	τ_v	0.2	*imposed*
- Rate of job destruction	σ	0.1	Shimer (2005)
Health			
- Scale parameter in health function	η	0.5	*imposed*
- Returns in healthcare activities	ψ	0.5	*imposed*
- Depreciation rate of health capital	δ_0	0.025	*matches steady-state target*
- Intensity of pollution externality on health depreciation	ζ	0.1	*imposed*
Pollution			
- Pollution capacity of physical capital	π_k	0.07	*imposed*
- Pollution capacity of final output	π_y	0.1	*imposed*
- Tax rate on capital income	τ_k	0.3	Gomme and Rupert (2007); McDaniel (2007)
- Environmental tax rate on final output	τ_y	0.005	OECD statistics tables
- Share of the environmental tax revenues used in abatements activities	β	0.5	*imposed*
- Nature regeneration rate	γ	0.05	*imposed*

Preference and technology parameters: We follow the RBC literature to set the capital's share in income α at 1/3. The rate of physical capital depreciation is chosen to be consistent with Gomme and Rupert (2007).

Following recommendations by Chetty et al. (2011) to be consistent with micro-data, we set $\varphi = 2$, which implies a Frisch labor supply elasticity of 0.5 as widely adopted by the literature. Disutility of work χ is calibrated in order to insure that total leisure time is close to two third of individual time (Prescott, 2004) and ρ is chosen to obtain an annual pre-tax interest rate equal to 4% as usual in the literature. The weight of health in utility μ_h is in line with the range of values considered by French (2005). Productivity parameter Z is set to obtain $\theta^\star = 0.43$ as reported above.

Health parameters: It is quite difficult to get values for the scale parameter in health function η and the returns to healthcare activities ψ. We follow the literature studying the efficiency of health expenditures (Skinner et al., 2005; Garber and Skinner, 2008; Chandra et al., 2016; Chandra and Staiger, 2017) according to which health expenditures are quite inefficient especially in the USA. Therefore we choose $\eta = 0.5$ which is consistent with some empirical evidence[19] and decreasing returns to scale in health production ($\psi = 0.5$)[20] as benchmark values and we will investigate different values, in the robustness analysis.

We assume that the depreciation rate of health capital is defined as $\delta_h(P) = \delta_0 + \zeta\frac{1}{1+(a/P)^n}$, where δ_0 is the depreciation rate of health capital without pollution externality and $\zeta\frac{1}{1+(a/P)^n}$ is a sigmoïd function capturing the external effect of pollution on health depreciation. Parameter $\zeta \in [0, 1[$ measures the intensity of pollution externality, $n > 1$ captures the straightness of the sigmoïd and $a > 0$ is a scale parameter to configure the inflection point $a\left(\frac{n-1}{n+1}\right)^{1/n}$ of the sigmoïd. The sigmoïd function enables to capture the bounded and the S-shaped influence of pollution on health depreciation (see blue/plain curve in Figure 1). To calibrate the depreciation rate of health capital without pollution externality (δ_0), we use equation (26) $H^\star = \frac{\psi\delta_h(P^\star)}{\rho+\delta_h(P^\star)}\left(\frac{\mu_h}{1-\mu_h}\right) C^\star$. According to the World Bank statistics tables, final consumption in the US represented 68.01% of the 2014 GDP and according to OECD statistics tables, the voluntary health expenditures represented 8.4 %. As a result, ratio $\frac{\psi\delta_h(P^\star)}{\rho+\delta_h(P^\star)}\left(\frac{\mu_h}{1-\mu_h}\right)$ equal 8.4/68.01=12.35%. Abstracting from pollution externality on health, it gives a calibrated δ_0 at 0.025. We benchmark the influence of pollution on health depreciation as a smooth phenomenon choosing $\zeta = 0.1$ (meaning that the depreciation rate of health capital never exceeds 0.125), $a = 20$ and $n = 2$ to get a smooth detrimental impact of pollution on health.

Pollution parameters: OECD statistics tables on environmental policy instruments indicate that environmental taxation represents 0.47% of GDP in 2012 in

[19]The British Medical Journal Evidence Centre (2011) reports that less than 35% of procedures seems to be beneficial or likely to be beneficial. Skinner et al. (2001) shows that nearly 20 percent of total medical-care expenditure does not provide benefit to health.

[20]This is consistent with the theoretical literature about health production (Ehrlich and Chuma, 1990, amongst others) and the empirical evidence even if Galama et al. (2012) question the robustness of prior estimates in the empirical literature.

the US. Furthermore, the average environmental tax in OECD represents 1.09% of GDP in 2012, and the highest environmental tax rate is 2.20% of GDP in Denmark. We will use 0.5% of GDP for our benchmark environmental tax when output is the source of pollution. For the value of the environmental tax when physical capital is the source of pollution τ_k, we chose a value which is consistent with Gomme and Rupert (2007) and McDaniel (2007). The values of the other pollution parameters π_k, π_y and γ, are chosen as reasonable.[21] The share of environmental revenue used to fund abatement activities, β, is arbitrarily chosen to 0.5.

6.2 Benchmark results

We investigate three different scenarios of environmental policy aimed at reducing the level of pollution by around 5% in the case of a perfect market labor. Then, in the first scenario, the environmental tax on capital rises from 0.3 to 0.359 all things being equal, in the second scenario the environmental tax on output rises from 0.005 to 0.025 all things being equal, and in the third scenario the share of the environmental tax revenues used in abatement activities rises from 0.5 to 0.99. For both scenarios, we examine the impact of the environmental policy on the steady-state status and on the key variables[22] when labor market is assumed to be perfect and in the presence of frictions. The purpose is to get a sense of the magnitude of the new effects of environmental taxation from market frictions on health-status, output and welfare. Results are reported in Table 2.

Table 2: Simulation results - Benchmark Case (variations in %)

Policy	Labor market status	$\Delta P^\star$	$\Delta h^\star$	$\Delta Y^\star$	$\Delta W^\star$	$\Delta C^\star$	$\Delta H^\star$	$\Delta u^\star$
$\Delta^+\tau_k$	Perfect	-5.01	3.46	0.89	3.34	1.24	-0.48	–
$_{0.33\to 0.0359}$	Frictions	-5.14	3.35	0.75	3.36	1.10	-0.65	0.70
$\Delta^+\tau_y$	Perfect	-5.06	3.64	2.08	4.00	1.54	-0.20	–
$_{0.005\to 0.025}$	Frictions	-5.20	3.54	1.93	4.08	1.40	-0.37	0.89
$\Delta^+\beta$	Perfect	-5.00	3.41	4.55	2.36	1.16	-0.55	–
$_{0.5\to 0.99}$	Frictions	-5.10	3.29	4.44	2.28	1.03	-0.70	0

The sign of the effects of the environmental tax are not modified when frictions on labor market are taken into account. Nevertheless, the magnitude of these effects are different. Not taking into account frictions on labor market leads to overestimate the positive impact of environmental tax on health, output and consumption while it leads to underestimate the improvement in pollution and the positive impact on welfare. This result can be generalized whatever the type of environmental policy taken into account.

[21] Modifying chosen values of π_k, π_y, or γ does not modify significantly the results of the simulations. Proof upon request.

[22] Including lifetime welfare evaluated at the steady-state $W^\star$, using lifetime utility function (1).

Proposition 7. *According to our chosen parameter values, the existence of frictions on market labor reduces the health dividend of the environmental policy and its positive impact of final output, whatever the policy.*

Proof. From Table 2. □

Even if in our numerical simulations, differences in magnitude are not important between perfect labor market and imperfect labor market, it does not mean that implications for the society could not be sizable. These differences mainly come from general equilibrium mechanisms linked to the fact that increasing environmental tax (τ_k or τ_y) rises unemployment and as a consequence reduces the positive impact on final output and consumption. These reductions explain the best performance of the policy in terms of pollution decrease. Nevertheless, this positive effect does not translate in a better improvement in health because the rise in health due to the health pollution externality is limited by the reduction of the health-care expenditures.

While unemployment is not impacted by an increase in β, the share of the environmental tax revenue used for funding pollution abatement activities, nevertheless we obtain similar mechanisms because an increase in β crowds-out resources from production and health-care activities to abatement activities.

How the nature and the size of these effects are modified when parameter values are modified? We investigate this point in the following robustness analysis. We will focus on parameters for which no values are available in the literature, especially parameters associated with health production function (ψ, η and the shape of the pollution externality of health).[23]

6.3 Robustness analysis I: The size and the shape of the pollution externality on health

What becomes the health dividend of the environmental policy when the size and shape of the pollution externality on health is modified? Are our previous results comparing perfect and imperfect labor markets modified?

To get a sense of the magnitude of the health effects linked to pollution externality in health, we first consider the case where there is no pollution externality in health, by setting ζ to 0. Second, we investigate how the shape of the sigmoïd function chosen to represent the impact of pollution on health depreciation affects our result. Results are reported in Tables 3 and 4.

When the pollution externality on health is not taken into account ($\zeta = 0$), the positive impact of the environmental policy on pollution is highly over-estimated (twice more) and the detrimental effects on the economy are highly under-estimated: all key variables decrease at least by more than 2% and the negative effects are more important with imperfect labor markets. Especially, the effect on health is now negative, meaning that in our numerical simulations, the pollution externality on health more than compensates the decrease in health due to the fact that environmental

[23]Modifying parameter values for π_k, π_y, γ, σ, ξ_V or ρ does not affect significantly the results of the benchmark model simulations. Proof upon request.

Table 3: Robustness analysis without pollution externality on health - $\zeta = 0$ (variations in %)

Policy	Labor market status	$\Delta P^\star$	$\Delta h^\star$	$\Delta Y^\star$	$\Delta W^\star$	$\Delta C^\star$	$\Delta H^\star$	$\Delta u^\star$
$\Delta^+\tau_k$	Perfect	-10.23	-2.31	-4.65	-2.35	-4.57	-4.57	–
$_{0.33\to0.0359}$	Frictions	-10.31	-2.35	-4.73	-2.57	-4.65	-4.65	0.70
$\Delta^+\tau_y$	Perfect	-10.32	-2.19	-3.58	-2.12	-4.32	-4.32	–
$_{0.005\to0.025}$	Frictions	-10.41	-2.24	-3.68	-2.33	-4.42	-4.42	0.89
$\Delta^+\beta$	Perfect	-10.20	-2.34	-1.17	-2.73	-4.62	-4.62	–
$_{0.5\to0.99}$	Frictions	-10.21	-2.36	-1.18	-2.96	-4.66	-4.66	0

policy crowds-out resources (in particular health care expenditures) and rises unemployment leading to a stronger decrease in output.

A further insight of this exercise is that pollution externality on health creates a sort of "rebound effect" of the environmental policy by improving health and output and therefore leading to additional increase in pollution. Indeed, the increase in environmental tax reduces pollution to 5% in the presence of pollution externality on health (table 2) while it reduces pollution to more than 10% when there is no pollution externality on health.

Proposition 8. *The existence of a pollution externality on health creates a sort of "rebound effect" of the environmental policy. As a result, the greater the pollution externality on health the less efficient is the environmental policy on pollution reduction.*

Proof. See Table 3. □

The importance of the pollution externality effect for a global health dividend of the environmental policy requires to investigate the influence played by the shape of the pollution externality, captured by the sigmoïd function $\delta_h(P) = \delta_0 + \zeta \frac{1}{1+(a/P)^n}$. In Figure 1, we reported three sigmoïds with different shapes. These shapes capture three different values of the pollution externality on health. The benchmark case (blue/plain curve) captures a very smooth detrimental influence of pollution on health, the red/small dashed curve ($a = 2$) captures a fast and strong detrimental influence of pollution on health and the orange/medium dashed curve ($n = 5$) captures an intermediate case, with a slower and weaker influence of pollution on health than when $a = 2$ but a faster and stronger influence than in the benchmark case. Small black dots on each curve refer to the initial pollution level and large red dots are respective inflection points.[24] In Table 4, we report simulations for the three cases.

First of all, in the presence of a weak detrimental effect of pollution on health ($n = 5$), the health dividend is higher than in the benchmark case. One possible

[24]Initial pollution levels are endogenous and inflection points are given by $a\left(\frac{n-1}{n+1}\right)^{1/n}$.

Table 4: Robustness analysis for pollution externality on health (variations in %)

	Policy	Labor market status	$\Delta P^\star$	$\Delta h^\star$	$\Delta Y^\star$	$\Delta W^\star$	$\Delta C^\star$	$\Delta H^\star$	$\Delta u^\star$
	$\Delta^+\tau_k$	Perfect	-5.08	8.01	3.96	6.31	4.64	0.72	–
	$0.33\to0.0386$	Frictions	-5.49	7.60	3.51	6.00	4.17	0.25	1.05
		Frictions high.	-5.97	7.11	2.99	5.59	3.62	-0.26	1.01
	$\Delta^+\tau_y$	Perfect	–5.00	8.14	5.72	6.89	5.07	1.19	–
$n=5$	$0.005\to0.034$	Frictions	-5.41	7.75	5.26	6.61	4.61	0.72	1.30
		Frictions high.	-5.89	7.27	4.73	6.25	4.07	0.22	1.25
	$\Delta^+\beta$(2)	Perfect	-3.41	5.36	6.52	3.65	3.10	0.47	–
	$0.5\to1$	Frictions	-3.66	5.08	6.25	3.41	2.79	0.17	0
		Frictions high.	-3.94	4.75	5.93	3.11	2.44	-0.15	0
	$\Delta^+\tau_k$	Perfect	-5.05	1.96	-0.13	-1.45	0.07	-0.06	–
	$0.33\to0.035$	Frictions	-4.93	2.14	-0.001	-1.56	0.21	-0.52	0.59
		Frictions high.	-4.82	2.28	0.11	-1.63	0.32	-0.45	0.56
	$\Delta^+\tau_y$	Perfect	-5.15	2.12	0.85	-2.07	0.31	-0.38	–
$a=2$	$0.005\to0.022$	Frictions	-5.03	2.30	0.97	-2.14	0.45	-0.29	0.75
		Frictions high.	-4.92	2.46	1.08	-2.18	0.57	-0.22	0.73
	$\Delta^+\beta$	Perfect	-4.99	1.90	2.87	-0.49	-0.01	-0.67	–
	$0.5\to0.91$	Frictions	-4.84	2.06	3.04	-0.65	0.14	-0.57	0
		Frictions high.	-4.70	2.20	3.18	-0.77	0.26	-0.77	0

(1) Captured by $M_0 = 1$ as a remplacement for the benchmark $M_0 = 1.98$.
(2) β can not be higher than 1.

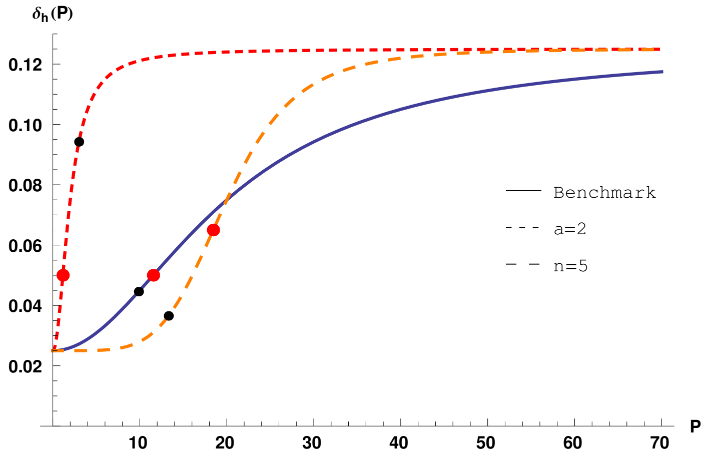
explanation is that the initial level of pollution is higher (see Figure 1) and in the "increasing returns" area. As a result, a 5% decrease in pollution leads to greater health improvements than in the benchmark case. Conversely, in the presence of a strong detrimental effect of pollution on health ($a = 2$), the initial level of pollution is low and in the "decreasing returns" area, as a consequence a 5% decrease in pollution leads to smaller health improvements than in the benchmark case.

Second, when $n = 5$ (respectively $a = 2$), the existence of frictions on the labor market leads to a lower (resp. higher) magnitude of the health dividend than in the case of perfect labor market. It means that, according to the shape of the influence of pollution on health, labor market frictions could affect differently health gains from environmental policy.

To confirm this result, we investigate the case where frictions are more important in labor market. It is captured by decreasing the value of M_0 (from 1.98 to 1): everything be equal, because with higher frictions, the probability for an agent to match is lower. We compute simulations for both cases (see Table 4).

Proposition 9. *In economies where there is a great (respectively small) room for health improvement due to a given reduction of pollution, more frictions on labor market tend to increase (resp. to reduce) the health dividend of the environmental policy, whatever this policy.*

Figure 1: Different shapes for pollution externality on health $\delta_h(P)$



Proof. See Table 4. □

Proposition 9 comes from the fact that $\delta_h(P)$ positively affects the split of global expenditures towards healthcare expenditures and not consumption. This Proposition has interesting implications when we investigate the ability of a country to improve health level by reducing its pollution. China, for example, suffers from very high levels of air pollution and huge detrimental effects on health. As a result, there is a great room of health improvement due to pollution reduction. Furthermore, labor market is characterized by serious frictions: labor shortage in some sectors co-existing with high rate of unemployment in others, with an average of 19 months of unemployment duration (Liu, 2013; You and Wang, 2018). As a consequence, according to Proposition 9, a reduction in pollution should lead to greater improvements in health. But it also means, from Proposition 8, that the gains in terms of pollution reduction could be lower than expected. These elements must be taken into account before implementing the environmental policy to maximize its efficiency both in terms of pollution reduction and health improvements.

6.4 Robustness analysis II: The health production function (η and ψ)

After investigating the role played by the pollution externality on our results, we focus on two key parameters of the health production function: the scale parameter η and the level of returns to scale of healthcare expenditures ψ.

Previously, we highlighted the importance of ψ in Proposition 2 but, as already mentioned, there is no consensus about the existence of decreasing returns to scale in healthcare activities (see Galama et al., 2012, for a discussion) and the canonical health production function by Grossman (1972) exhibits constant returns to scale. That is the reason why, we will study two cases: $\psi = 0.99$ which means quite constant returns to scale[25] and $\psi = 0.1 < \frac{1}{1+\varphi}$ which means high decreasing returns.

[25]In our framework $\psi \in]0, 1[$.

Table 5: Robustness analysis for ψ (variations in %)

	Policy	Labor market status	$\Delta P^\star$	$\Delta h^\star$	$\Delta Y^\star$	$\Delta W^\star$	$\Delta C^\star$	$\Delta H^\star$	$\Delta u^\star$
$\psi = 0.99$	$\Delta^+\tau_k$	Perfect	-7.65	0.67	-1.91	-2.45	-1.31	-3.47	–
	$0.33 \to 0.0359$	Frictions	-10.71	-2.62	-5.16	103.82	-4.56	-6.87	0.70
	$\Delta^+\tau_y$	Perfect	-7.27	1.31	-0.30	2.72	-0.58	-2.64	–
	$0.005 \to 0.025$	Frictions	-10.19	-1.83	-3.44	74.36	-3.69	-5.91	0.89
	$\Delta^+\beta$	Perfect	-7.74	0.52	1.53	-7.10	-1.49	-3.67	–
	$0.5 \to 0.99$	Frictions	-10.74	-2.75	-1.77	125.56	-4.70	-7.02	0
$\psi = 0.1$	$\Delta^+\tau_k$	Perfect	-4.73	3.70	1.20	2.26	1.34	-0.22	–
	$0.33 \to 0.0359$	Frictions	-4.76	3.71	2.29	1.16	1.31	-0.28	0.70
	$\Delta^+\tau_y$	Perfect	-4.84	3.81	2.32	2.59	1.58	-0.02	–
	$0.005 \to 0.025$	Frictions	-4.88	3.83	2.28	2.64	1.54	-0.09	0.89
	$\Delta^+\beta$	Perfect	-4.70	3.67	4.88	1.72	1.29	-0.26	–
	$0.5 \to 0.99$	Frictions	-4.70	3.66	4.88	1.71	1.25	-0.32	0

Proposition 10. *According to our chosen set of parameter values, in the presence of quite constant returns to scale in healthcare activities, when frictions on labor market and wage bargain are taken into account, the effect of a tighter environmental tax on health becomes negative and sizable, while it is positive and small with perfect labor market.*

Proof. See Table 5. □

Proposition 10 states that the existence of frictions on labor market modifies deeply the health dividend of environmental policy according to the nature of returns to scale in health activities. Especially, when returns to scale are quite constant (but decreasing), the health dividend becomes negative and sizable. Indeed, a tighter environmental tax or a greater part of tax revenue towards abatement activities reduce resources available in the economy and as a consequence leads to a higher cost of posting vacant job. As a result, unemployment rises and incomes diminish leading to a decrease in healthcare expenditures. This impact of this drop on health status is amplified when returns to scale in healthcare activities are quite constant, leading to a greater decrease in health status, everything being equal. While with perfect labor market the global effect was positive but small, the negative impact on health introduced by frictions and constant returns to scale leads to a sizable negative impact of the environmental policy on the steady-state health status.

When returns to scale are highly decreasing in healthcare activities ($\psi = 0.1$), we obtain the same results than for the benchmark case. It is interesting to note, related to Proposition 3.2 that the positive impact of a tighter τ_k on final output $Y^\star$ is higher in the presence of frictions, meaning that, even when $\psi < \frac{1}{1+\varphi}$, the crowding-out effect of the environmental tax is reduced with respect to the perfect market labor economy.[26]

[26] We can infer this result from Table 6 column 6 last lines because the health effect remains

When η, the scale parameter in health production function, rises, health dividend from environmental policy is greater and over-estimated when frictions on labor market are not taken into account. It means that a greater scale parameter rises the health impact of the environmental policy with respect to the perfect labor market case.

Table 6: Robustness analysis for η (variations in %)

	Policy	Labor market status	$\Delta P^\star$	$\Delta h^\star$	$\Delta Y^\star$	$\Delta W^\star$	$\Delta C^\star$	$\Delta H^\star$	$\Delta u^\star$
$\eta = 1$	$\Delta^+\tau_k$	Perfect	-4.95	3.52	0.96	1.75	1.27	0.03	–
	$0.33 \to 0.0359$	Frictions	-4.92	3.59	0.99	1.85	1.30	0.002	0.70
	$\Delta^+\tau_y$	Perfect	-4.99	3.70	2.15	2.09	1.58	0.32	–
	$0.005 \to 0.025$	Frictions	-4.97	3.78	2.17	2.21	1.61	0.29	0.89
	$\Delta^+\beta$	Perfect	-4.93	3.47	4.62	1.23	1.20	-0.04	–
	$0.5 \to 0.99$	Frictions	-4.87	3.52	4.69	1.29	1.23	-0.06	0
$\eta = 0.21$	$\Delta^+\tau_k$	Perfect	-7.92	0.25	-2.19	3.16	-1.99	-3.00	–
	$0.33 \to 0.0359$	Frictions	-8.25	-0.08	-2.55	3.44	-2.36	-3.27	0.70
	$\Delta^+\tau_y$	Perfect	-7.99	0.39	-1.08	2.01	-1.72	-3.02	–
	$0.005 \to 0.025$	Frictions	-8.34	0.06	-1.45	2.51	-2.10	-3.02	0.89
	$\Delta^+\beta$	Perfect	-7.90	0.21	1.36	4.92	-2.05	4.92	–
	$0.5 \to 0.99$	Frictions	-8.17	-0.11	1.06	4.87	-2.39	4.87	0

6.5 How labor policies affect the environment and health?

Finally, we investigate how labor market policies affect the environment and health. We consider three different labor policies: a decrease in the rate of unemployment benefits (τ_u), a decrease in the tax rate on labor income (τ_w) and a increase in subventions to post vacant job (τ_v). For both policies, we examine how simulation results are modified when there is no pollution externality on health ($\zeta = 0$), when the detrimental impact of pollution on health is strong from low increase in pollution ($a = 2$) and in the presence of low decreasing returns to scale in healthcare activities ($\psi = 0.9$). Results are reported in Table 7.

All labor policies have a strong impact of unemployment, reducing the unemployment rate between quite -8% for $\Delta^-\tau_w$ to -15% for $\Delta^-\tau_u$. Nevertheless, labor policies are rather negative for pollution and health in the benchmark case, even if the decrease in unemployment benefit leads to a small decrease in pollution. Conversely, the decrease in the tax rate of labor income entails a great increase in pollution and a decrease in health status while healthcare expenditures rise. As highlighted in Proposition 8, in the absence of pollution externality on health, we obtain a strong positive impact of health, even if pollution stock strongly rises by almost 16%. In

quite the same with and without frictions (3.71% vs 3.70%, 3.83% vs 3.86% and 3.66% vs 3.67%).

Table 7: Impacts of labor market policies (variations in %)

Policy		$\Delta P^\star$	$\Delta h^\star$	$\Delta Y^\star$	$\Delta W^\star$	$\Delta C^\star$	$\Delta H^\star$	$\Delta u^\star$
$\Delta^- \tau_u$	Bench.	-0.23	-0.25	-0.23	-0.12	-0.73	-0.81	-15.94
$0.5 \to 0.25$	$\zeta = 0$	-0.47	-0.49	-0.47	-0.23	-0.98	-0.98	-15.94
	$a = 2$	-0.26	-0.29	-0.26	0.14	-0.77	-0.81	-15.94
	$\psi = 0.9$	-1.07	-1.07	-1.07	-4.52	-1.51	-1.81	15.94
$\Delta^- \tau_w$	Bench	7.29	-0.58	7.29	-0.14	6.68	9.21	-7.91
$0.2 \to 0$	$\zeta = 0$	15.94	7.56	15.94	5.51	15.68	15.68	-7.91
	$a = 2$	8.85	0.91	8.85	-2.04	8.39	9.58	-7.91
	$\psi = 0.9$	17.77	8.85	17.77	44.82	16.23	22.03	-7.91
$\Delta^+ \tau_v$	Bench	0.65	-0.23	0.65	0.029	0.23	0.44	-12.77
$0.2 \to 0.5$	$\zeta = 0$	1.36	0.48	1.36	0.51	.097	0.97	-12.77
	$a = 2$	0.76	-0.12	0.76	-0.21	0.35	0.35	-12.77
	$\psi = 0.9$	1.25	0.35	1.25	3.11	0.78	1.13	-12.77

the same way, in the presence of small decreasing returns to scale in healthcare activities ($\psi = 0.9$), the rise in healthcare expenditures generates greater benefits of $\Delta^- \tau_w$ in terms of health which offset the detrimental impact of the almost 18% increase in pollution stock. Health status rises by almost 9%.

One more time, the outcome of policies, here labor policies, in terms of pollution reduction and health improvement is strongly conditioned by the importance and the shape of the pollution externality on health and by the returns to scale in healthcare activities.

Proposition 11. *According to our chosen parameter values, labor market policies aimed at reducing unemployment have sizable impacts on pollution reduction and health improvements. In particular, the sign of these impacts (positive or negative) depends on i) the nature of the policy, ii) the size and the shape of the pollution externality on health and iii) the returns to scale in healthcare activities.*

Proof. See Table 7. □

The most efficient labor market policy in terms of unemployment rate reduction consists in lowering the rate of subsidy to unemployment (τ_u). But it will generate few gains in terms of pollution reduction while it reduces health-status. However, according to our chosen benchmark parameter values, it appears as the most beneficial policy for pollution and health, compared to reducing the rate of tax on income or increasing the rate of subsidy to vacant job.

7 Conclusion

The aim of this article was to re-examine the health effect of the environmental policy in the presence of labor market imperfections. For that purpose we developed an intertemporal general equilibrium search model of unemployment with pollution and endogenous health-status, which is coherent with the empirical evidence that unemployment is detrimental to health.

The contribution of the article is manyfold.[27] A first major result is that a tighter environmental tax (on final output or physical capital) affects labor market equilibrium through different channels: *i)* by rising the tightness in the labor market, *ii)* by reducing the transmission of labor productivity gains towards wage, *iii)* by reducing the incentives to search for a job and *iv)* by increasing the cost payed by a firm when it posts a vacancy job. Then, a tighter environmental tax increases the steady-state unemployment rate, whatever the source of pollution (physical capital or final output) and more frictions on labor market associated with wage bargain, reduce the steady-state level of output, for a given environmental tax and reinforces the negative impact of a tighter environmental tax on final output.

A second major result is that, not taking into account frictions on labor market leads to overestimate the positive impact of environmental tax on health, output and consumption while it leads to underestimate the improvement in pollution and the positive impact on welfare, whatever the environmental policy.

A third major result is that the "size" of pollution externality on health plays a crucial role. On one hand, such an externality creates a sort of "rebound effect" of the environmental policy and as a consequence, the greater the pollution externality on health the less efficient is the environmental policy in terms of pollution reduction, because improvements in health due to the environmental policy rise the efficiency of labor, free resources from healthcare expenditures, and therefore increase output and consumption. On other hand, in economies which experiment great negative externality of pollution on health and suffer from great frictions on labor market, like China and most of the developed countries, it is expected that pollution reduction will generate a higher health dividend because frictions contribute to reduce activity and therefore pollution, and a given decrease in pollution generates a greater improvement in health. This mechanism is fostered by higher returns to scale in the health sector.

Finally, an another important contribution of this article concerns the impact of labor market policies on pollution reduction and health improvements. According to our chosen parameter values, our numerical exercises show that labor market policies aimed at reducing unemployment have sizable impacts on pollution reduction and health improvements. In particular, the sign of these impacts (positive or negative) depends on *i)* the nature of the policy, *ii)* the size and the shape of the pollution externality on health and *iii)* the returns to scale in healthcare activities. In our benchmark case, the most efficient labor market policy in terms of unemployment rate reduction consists in lowering the rate of subsidy to unemployment. It is the most beneficial policy in terms of pollution and health, compared to reducing the rate of tax on income or increasing the rate of subsidy to vacant job.

Our article calls for further investigations. The dynamics of the model has to be studied to understand the short-term adjustments in terms of employment, pollution

[27] In the following, we just list some of the main results. For all contributions, see the Introduction.

and health. Our modeling could be enriched by introducing an explicit abatement sector (like in Hafstead and Williams III, 2018) in order to encounter for labor and physical capital sectorial re-allocations associated with the environmental policy and their impacts in terms of unemployment and health. At empirical level, the two negative effects of environmental tax on health arising from labor market imperfections and the global effect of the environmental tax on health should be evaluated, in order to re-assess the inter-related effects of labor market policy and environmental policy on both unemployment, the environmental and health.

Finally, our theoretical framework calls for the elaboration of an integrated policy-making (combining labor market and environmental protection policy measures) to improve the outcomes of both environmental regulation and labor market policies.

APPENDIX

A Resolution of the general model

Here, we solve the model taking into account both τ_y and τ_k in the same framework. Furthermore, we make several assumptions with respect to the model presented in the main text, to enrich it:

1. We introduce T as the time used in health-enhancing activities by the representative household. This time can be viewed as sport time, time for taking medicine,...[28] As a consequence leisure time becomes $1 - T - U - L_s$.

2. Ecology is captured by the stock of pollution P which rises with the flow of pollution emissions E and is reduced by abatement activities denoted by A, such as the stock of pollution evolves according to the law:

$$\dot{P} = \Omega(E, A) - \gamma P \tag{A.1}$$

where $\gamma > 0$ is the nature regeneration rate, and $\mathit{\Omega}(E, A)$ is the net flow of pollution (with $\mathit{\Omega}_1 > 0$ and $\mathit{\Omega}_2 < 0$). As usual in environmental economics, we consider two different sources of pollution: final output (with a polluting capacity $\pi_y \in [0, 1]$) and physical capital (with a polluting capacity $\pi_k \in [0, 1]$). As a result, emissions is defined as $E = \pi_y Y + \pi_k K$.

3. Each unemployed agent earns unemployment benefits defined as a part $\tau_u \in [0, 1]$ of the efficiency wage $\tilde{w}$, such that the overall unemployment benefits for the representative household is $\tau_u \tilde{w} U$.

The representative household chooses (C, L_s, U, T, H) and the supply of capital K_s to solve

$$\begin{aligned}
&\max_{C,h,L_s,U,H,K_s,T} \int_t^{\infty} e^{-\rho(z-t)} u\left(C, 1 - T - U - L_s, h\right) dz \\
&s.t. \\
&\dot{K}_s = (1 - \tau_k) r K_s + \mathit{\Pi} + (1 - \tau_w)\tilde{w} L_s - C - H + \tau_u \tilde{w} U + S \\
&\dot{L}_s = mU - \sigma L_s \\
&\dot{h} = \mathcal{G}(H, T) - \delta_h(P) h \\
&K_s(0) = K_{s0},\ L_s(0) = L_{s0},\ h(0) = h_0 \ given
\end{aligned}$$

The current Hamiltonian is:

$$\begin{aligned}
\mathcal{H}^{ho} &= u\left(C, 1 - T - U - L_s, h\right) \\
&+ \lambda_K \left[(1 - \tau_k) r K_s + (1 - \tau_w)\tilde{w} L_s - C - H + \tau_u \tilde{w} U + S\right] \\
&\qquad\qquad + \lambda_L \left[mU - \sigma L_s\right] + \lambda_h \left[\mathcal{G}(H, T) - \delta_h(P) h\right]
\end{aligned}$$

with transversality conditions such that:

$$\lim_{z \to \infty} \lambda_K K_s e^{\rho(t-z)} = \lim_{z \to \infty} \lambda_L L_s e^{\rho(t-z)} = \lim_{z \to \infty} \lambda_h h e^{\rho(t-z)} = 0$$

[28]For a justification and some examples, please see Mathieu-Bolh and Pautrel (2016) amongst others.

First-order conditions are:[29]

$$\frac{\partial \mathcal{H}^{ho}}{\partial C} = 0 \qquad : \qquad u_1 - \lambda_K = 0 \tag{A.2}$$

$$\frac{\partial \mathcal{H}^{ho}}{\partial U} = 0 \qquad : \qquad \tau_u \tilde{w} \lambda_K - u_2 + m\lambda_L = 0 \tag{A.3}$$

$$\frac{\partial \mathcal{H}^{ho}}{\partial H} = 0 \qquad : \qquad -\lambda_K + \mathcal{G}_1(H,T)\lambda_h = 0 \tag{A.4}$$

$$\frac{\partial \mathcal{H}^{ho}}{\partial T} = 0 \qquad : \qquad -u_2 + \mathcal{G}_2(H,T)\lambda_h = 0 \tag{A.5}$$

$$\dot{\lambda}_K - \rho\lambda_K = -\frac{\partial \mathcal{H}^{ho}}{\partial K_s} = -(1-\tau_k)r\lambda_K \tag{A.6}$$

$$\dot{\lambda}_L - \rho\lambda_L = -\frac{\partial \mathcal{H}^{ho}}{\partial L_s} = u_2 - (1-\tau_w)\tilde{w}\lambda_K + \sigma\lambda_L \tag{A.7}$$

$$\dot{\lambda}_h - \rho\lambda_h = -\frac{\partial \mathcal{H}^{ho}}{\partial h} = -u_3 + \delta_h(P)\lambda_h \tag{A.8}$$

Rewriting first-order conditions, we get

$$\dot{C} = \frac{u_1}{u_{11}}\left[\rho - (1-\tau_k)r\right] \tag{A.9}$$

$$m\lambda_L = u_2 - \tau_u \tilde{w} u_1 \tag{A.10}$$

The marginal benefit of the employment to the household (the right-hand side) is equal to the opportunity cost of the employment (the left-hand side).

$$\lambda_L = \frac{(1-\tau_w)\tilde{w}u_1 - u_2 + \dot{\lambda}_L}{\rho + \sigma} \tag{A.11}$$

The capital value of the employment to the household (the left-hand side) is equal the present value of the clash flow generated by the employment $(1-\tau_w)\tilde{w}u_1 - u_2$ plus capital gains $\dot{\lambda}_L$, discounted by $\rho + \sigma$.

Finally,

$$\lambda_h = u_1/\mathcal{G}_1(H,T) \qquad \text{and} \qquad \lambda_h = u_2/\mathcal{G}_2(H,T) \tag{A.12}$$

that is

$$\frac{\mathcal{G}_1(H,T)}{\mathcal{G}_2(H,T)} = \frac{u_1}{u_2} \tag{A.13}$$

and

$$\dot{\lambda}_h = -u_3 + \left[\rho + \delta_h(P)\right]\lambda_h \tag{A.14}$$

[29]Recall that $\dfrac{\partial u\,(C,l,h)}{\partial i} = \dfrac{\partial u\,(C,l,h)}{\partial l}\dfrac{\partial l}{\partial i} = u_2 \times (-1)$, with $i = \{L_s, H\}$.

Program of the firm is:

$$\max_{K_d,E,V}\int_t^{\infty}\left[(1-\tau_y)Y-(1-\tau_v)\tilde{\xi}_V V-\tilde{w}L_d-(r+\delta)K_d\right]e^{(1-\tau_k)r(t-z)}dz$$
$$s.t.$$
$$\dot{L}_d = qV-\sigma L_d$$
$$Y=\mathcal{F}\left(K_d,hL_d,\right)$$
$$K_d(0)=K_{d0},\ L_d(0)=L_{d0}\ given$$

The current Hamiltonian is written as:

$$\mathcal{H}^f=(1-\tau_y)\mathcal{F}\left(K_d,hL_d\right)-(1-\tau_v)\tilde{\xi}_V V-\tilde{w}L_d-(r+\delta)K_d+\mu_L[qV-\sigma L_d]$$

The first-order conditions are

$$\frac{\partial\mathcal{H}^f}{\partial V}=0 \quad : \quad (1-\tau_v)\tilde{\xi}_V=\mu_L q \tag{A.15}$$
$$\frac{\partial\mathcal{H}^f}{\partial K_d}=0 \quad : \quad (1-\tau_y)\mathcal{F}_K=r+\delta \tag{A.16}$$
$$\dot{\mu}_L-(1-\tau_k)r\mu_L=-\frac{\partial\mathcal{H}^f}{\partial L_d}=-\left[(1-\tau_y)\mathcal{F}_L-\tilde{w}\right]+\sigma\mu_L \tag{A.17}$$

and transversality condition is

$$\lim_{z\to\infty}\mu_L L_d e^{(1-\tau_k)r(t-z)}=0$$

Rewriting first-order conditions, we get

$$(1-\tau_y)\mathcal{F}_K=r+\delta \tag{A.18}$$
$$\mu_L q=(1-\tau_v)\tilde{\xi}_V \tag{A.19}$$

The effective marginal cost of vacancy $\tilde{\xi}_V$ equals the marginal benefit of vacancy to the firm $\mu_L q$.

$$\mu_L=\frac{(1-\tau_y)\mathcal{F}_L-\tilde{w}+\dot{\mu}_L}{(1-\tau_k)r+\sigma} \tag{A.20}$$

The capital value of vacancy to the firm (the left-hand side) is equal the present value of the clash flow linked to vacancy $(1-\tau_y)\mathcal{F}_L-\tilde{w}$ plus capital gains $\dot{\mu}_L$, discounted by $(1-\tau_k)r+\sigma$.

The government budget is balanced at all times. A part $\beta\in]0,1[$ of the environmental tax revenues is used to fund abatement activities A(which used forgone output to be produced): $\beta\left(\tau_y Y+\tau_k rK\right)=A$. The remaining of the environmental tax revenue is used with the labor tax revenue to fund unemployment benefits, vacancy subsidies and lump-sum transfers:

$$(1-\beta)\left(\tau_y Y+\tau_k rK\right)+\tau_w\tilde{w}L=\tau_u\tilde{w}U+S+\tau_v\tilde{\xi}_V V \tag{A.21}$$

A.1 Steady-state equilibrium

In the steady-state equilibrium, we have $\dot{L}(t) = \dot{U}(t) = 0$ and $\dot{\mu_L}(t) = \dot{\mu_K}(t) = \dot{\lambda_K}(t) = \dot{\lambda_L}(t) = \dot{\lambda_h}(t) = 0$. From (A.2), C, H, T, U, L, V, K, Y are constant.

Utility function is:

$$u\left(C, 1 - U - L, h\right) \equiv \log\left(C^{1-\mu_h} h^{\mu_h}\right) - \chi \frac{(T + U + L)^{1+\varphi}}{1+\varphi}$$

Therefore, we have:

$$u_1 = \left(1 - \mu_h\right) C^{-1}$$
$$u_2 = -\chi \left(T + U + L\right)^{\varphi}$$
$$u_3 = \mu_h h^{-1}$$

Because we assumed that $\Omega(E, A) \equiv E - A$, it comes $\Omega(E, A) = \left(\pi_y - \beta\tau_y\right) Y + \left(\pi_k - \beta\tau_k r\right) K$. At the steady-state, $\dot{P} = 0$ implies from (A.1):

$$P^\star = \frac{1}{\gamma}\left[\left(\pi_y - \beta\tau_y\right) Y^\star + \left(\pi_k - \beta\tau_k r^\star\right) K^\star\right] \tag{A.22}$$

Furthermore, we can define[30]

$$\mathcal{G}(H, T) \equiv \eta H^{\psi} T^{\iota} \qquad \text{with} \qquad (\psi, \iota) \in]0, 1[$$

and therefore

$$\mathcal{G}_1(H, T) = \eta\psi H^{\psi-1}$$
$$\mathcal{G}_2(H, T) = \eta\iota T^{\iota-1}$$

Then from (A.13) $\dfrac{\left(1 - \mu_h\right)\chi\left(T + U + L\right)^{\varphi}}{C} = \dfrac{\psi}{\iota}\left(\dfrac{H}{T}\right)^{\sigma_{\mathcal{G}}-1}$ that is

$$H = \left[\frac{\psi C}{\iota\left(1 - \mu_h\right)\chi\left(T + U + L\right)^{\varphi}}\right]^{1/(1-\sigma_{\mathcal{G}})} T \tag{A.23}$$

Because $\dot{\lambda}_h = 0$, from equations (A.12) and (A.14), we can express the expenditures in health care as a proportion $\mathcal{E}(P^\star) \in]0, 1[$ of the steady-state consumption level $C^\star$ which negatively depends on the environmental tax and :

$$H^\star = \mathcal{E}(P^\star) C^\star \qquad \text{with } \mathcal{E}(P^\star) \equiv \frac{\psi\delta_h(P^\star)}{\rho + \delta_h(P^\star)}\left(\frac{\mu_h}{1 - \mu_h}\right) \tag{A.24}$$

As a consequence, equation (A.24) gives the implicit expression of $T^\star$:

$$\mathcal{E}(P^\star)\frac{\iota\left(1 - \mu_h\right)}{\chi\psi}\left(T^\star + U^\star + L^\star\right)^{-\varphi} = T^\star \tag{A.25}$$

[30]To keep the model tractable, we assume that health-care expenditures et health-enhancing time are unitary substitutes.

Because $\dot{C} = 0$, it comes from (A.9), $(1-\tau_k)r = \rho$ and therefore equation (A.16) enables us to express capital per efficient unit of labor ($k \equiv K/(hL)$) at the steady-state as a function of the environmental tax:

$$k^\star = f(\tau_k)g(\tau_y) \tag{A.26}$$

where $f(\tau_k) \equiv \left[\frac{Z\alpha}{\frac{\rho}{1-\tau_k}+\delta}\right]^{1/(1-\alpha)}$ and $g(\tau_y) = (1-\tau_y)^{1/(1-\alpha)}$.

Because $\dot{\lambda}_L = 0$, we obtain from (A.10) and (A.11):

$$u_2^\star(\rho+\sigma+m(\theta^\star)) = u_1^\star \tilde{w}^\star \left[m(\theta^\star)(1-\tau_w) + (\sigma+\rho)\tau_u\right] \tag{A.27}$$

Putting this expression in (14) gives:

$$\tilde{w}^\star = \Phi(\theta^\star)(1-\tau_y)\mathcal{F}_L^\star \qquad \text{where } \Phi(\theta^\star) \equiv \frac{\phi(\rho+\sigma+m(\theta^\star))(1-\tau_w)}{(\rho+\sigma+m(\theta^\star)\phi)(1-\tau_w)-(1-\phi)(\sigma+\rho)\tau_u} < 1 \tag{A.28}$$

and $\Phi'(\theta^\star) > 0$.

Recalling that a variable $\tilde{x}$ expressed in efficiency units can by written as $h \cdot x$, and using (9), (A.28) and (A.26), we can express the wage rate as:

$$w^\star = \Phi(\theta^\star)(1-\alpha)Zf(\tau_k)^\alpha g(\tau_y) \tag{A.29}$$

Because $\dot{\mu_L} = 0$, from (A.19), (A.20) and (A.29):

$$(1-\alpha)Zf(\tau_k)^\alpha g(\tau_y) = \frac{\theta^\star(\rho+\sigma)(1-\tau_v)\xi_V}{m(\theta^\star)\left[1-\Phi(\theta^\star)\right]} \tag{A.30}$$

This equality defines the tightness of labor market as a function of the environmental tax: $\theta^\star = \Theta(\tau_y, \tau_k)$ with $\Theta'(\tau_i) < 0$ $(i = y, k)$.

Because $\dot{L} = 0$, using the definition of $m(\theta)$, it comes

$$U^\star = \frac{\sigma}{m(\theta^\star)}L^\star \tag{A.31}$$

Replacing by the expressions of u_1 and u_2 in equation (A.27) and using (A.28) and (A.31), we obtain

$$C^\star = \mathcal{A}_1(\theta^\star, \tau_y, \tau_k)h^\star\left(\left(\frac{\sigma}{m(\theta^\star)}+1\right)^{-1}T^\star + L^\star\right)^{-\varphi}$$

$$\text{where } \mathcal{A}_1(\theta^\star, \tau_y, \tau_k) \equiv (1-\alpha)Zf(\tau_k)^\alpha g(\tau_y)\left(\frac{1-\mu_h}{\chi}\right)\Lambda_1(\theta^\star)$$

$$\text{and } \Lambda_1(\theta^\star) \equiv \Phi(\theta^\star)\frac{(1-\tau_w)m(\theta^\star)+(\sigma+\rho)\tau_u}{\sigma+\rho+m(\theta^\star)}\left(\frac{\sigma}{m(\theta^\star)}+1\right)^{-\varphi} \tag{A.32}$$

Because $\dot{K} = 0$, using (A.21), (A.31) and (4) enables us to define a second relation between $C^\star$ and $L^\star$:

$$C^\star = \mathcal{A}_2(\theta^\star, \tau_y, \tau_k, P^\star) h^\star L^\star$$
$$\text{where } \mathcal{A}_2(\theta^\star, \tau_y, \tau_k, P^\star) \equiv \frac{\left[Z\left(\frac{1-\beta\tau_y}{1-\tau_y}\right) - \left(\delta + \beta\frac{\tau_k}{1-\tau_k}\rho\right) f(\tau_k)^{1-\alpha}\right] f(\tau_k)^\alpha g(\tau_y) - \Lambda_2(\theta^\star)}{1 + \mathcal{E}(P^\star)}$$
$$\text{and } \Lambda_2(\theta^\star) \equiv \frac{\sigma\theta^\star}{m(\theta^\star)}(1-\tau_v)\xi_V \quad \text{(A.33)}$$

Therefore, (A.32) and (A.33), with (A.25), give:

$$L^\star = \frac{\mathcal{A}(\theta^\star, \tau_y, \tau_k, P^\star)}{[\mathcal{B}\mathcal{E}(P^\star) + \mathcal{A}(\theta^\star, \tau_y, \tau_k, P^\star)]^{\frac{\varphi}{1+\varphi}}} \quad \text{(A.34)}$$

$$T^\star = \frac{\mathcal{B}\mathcal{E}(P^\star)}{[\mathcal{B}\mathcal{E}(P^\star) + \mathcal{A}(\theta^\star, \tau_y, \tau_k, P^\star)]^{\frac{\varphi}{1+\varphi}}} \quad \text{(A.35)}$$

where

$$\begin{cases} \mathcal{A}(\theta^\star, \tau_y, \tau_k, P^\star) \equiv \frac{\mathcal{A}_1(\theta^\star, \tau_y, \tau_k)}{\mathcal{A}_2(\theta^\star, \tau_y, \tau_k, P^\star)} = \frac{(1-\alpha)Z(1+\mathcal{E}(P^\star))(1-\mu_h)\Lambda_1(\theta^\star)}{\chi\left[Z\left(\frac{1-\beta\tau_y}{1-\tau_y}\right) - \left(\delta+\beta\frac{\tau_k}{1-\tau_k}\rho\right) f(\tau_k)^{1-\alpha} - \frac{\Lambda_2(\theta^\star)}{f(\tau_k)^\alpha}\right]} \\ \mathcal{B} \equiv \frac{(1-\mu_h)\iota}{\chi\psi} \end{cases}$$

Because $\dot{h} = 0$ at the steady-state, equation (3) gives $h^\star = \eta\dfrac{\mathcal{E}(P^\star)^\psi C^{\star\psi} T^{\star\iota}}{\delta_h(P^\star)}$. Then, from (A.33) and the fact that $\tilde{\xi}_V = h\xi_V$:

$$C^\star = \left[\frac{\eta\mathcal{E}(P^\star)^{\psi+\iota}}{\delta_h(P^\star)} \frac{\mathcal{A}_1(\theta^\star, \tau_y, \tau_k)\mathcal{B}^\iota}{[\mathcal{B}\mathcal{E}(P^\star) + \mathcal{A}(\theta^\star, \tau_y, \tau_k, P^\star)]^{\frac{\varphi(1+\iota)}{1+\varphi}}}\right]^{1/(1-\psi)}$$

and then

$$h^\star = \left[\frac{\eta\mathcal{E}(P^\star)^{\psi+\iota}}{\delta_h(P^\star)} \frac{\mathcal{A}_1(\theta^\star, \tau_y, \tau_k)^\psi\mathcal{B}^\iota}{[\mathcal{B}\mathcal{E}(P^\star) + \mathcal{A}(\theta^\star, \tau_y, \tau_k, P^\star)]^{\frac{\varphi(\psi+\iota)}{1+\varphi}}}\right]^{1/(1-\psi)} \quad \text{(A.36)}$$

Finally, output per capita at steady-state is given by:

$$Y^\star = \mathcal{Y}(P^\star, \tau_y, \tau_k) \equiv Z f(\tau_k)^\alpha g(\tau_y)^\alpha \left[\frac{\eta\mathcal{E}(P^\star)^{\psi+\iota}\mathcal{B}^\iota}{\delta_h(P^\star)}\right]^{\frac{1}{1-\psi}}$$
$$\times \frac{\mathcal{A}(\theta^\star, \tau_y, \tau_k, P^\star)\mathcal{A}_1(\theta^\star, \tau_y, \tau_k)^{\frac{\psi}{1-\psi}}}{[\mathcal{B}\mathcal{E}(P^\star) + \mathcal{A}(\theta^\star, \tau_y, \tau_k, P^\star)]^{\frac{\varphi(1+\iota)}{(1+\varphi)(1-\psi)}}} \quad \text{(A.37)}$$

And $P^\star$ is defined by:

$$\gamma P^\star - \left[\pi_y - \beta\tau_y + \left(\pi_k - \beta\frac{\tau_k\rho}{1-\tau_k}\right)\frac{f(\tau_k)^{1-\alpha} g(\tau_y)^{1-\alpha}}{Z}\right]\mathcal{Y}(P^\star, \tau_y, \tau_k) = 0 \quad \text{(A.38)}$$

Therefore, the system of equations (A.37) and (A.38) define $Y^\star$ and $P^\star$ as a function of τ_y and τ_k.

B Demonstration of equation (35)

Using (A.22) and (33), $P^\star$ is the solution of

$$\gamma P^\star - \left(\pi_k - \beta\frac{\tau_k\rho}{1-\tau_k}\right) f(\tau_k)^{1-\alpha}\mathcal{Y}(P^\star,\tau_k)/Z = 0 \tag{34'}$$

Because when $1-(1+\varphi)\psi < 0$, $\mathcal{Y}(P^\star,\tau_k)$ is a decreasing function of $P^\star$ and τ_k, the equation is increasing in $P^\star$ and τ_k. Therefore, when the unique solution $P^\star$ exists, it is decreasing in τ_k, from the theorem of the implicit functions.

When $1-(1+\varphi)\psi > 0$, equation (34') can be written as (using 33):

$$\begin{aligned}&\gamma P^{\star(1+\varphi)(1-\psi)}\left[\frac{(1+\mathcal{E}(P^\star))}{Z-\left(\delta+\beta\frac{\tau_k}{1-\tau_k}\rho\right)f(\tau_k)^{1-\alpha}-\frac{\mathit{\Lambda}_2(\mathit{\Theta}(\tau_k))}{f(\tau_k)^\alpha}}\right]^{(1+\varphi)\psi-1}\\ &\qquad -(1-\alpha)\left(\frac{1-\mu_h}{\chi}\right)\left(Zf(\tau_k)^\alpha\frac{\eta\mathcal{E}(P^\star)^\psi}{\delta_h(P^\star)}\right)^{1+\varphi}\mathit{\Lambda}_1\left(\mathit{\Theta}(\tau_k)\right)=0\end{aligned}$$

Because the term into bracket on the first line is increasing in $P^\star$ and decreasing in τ_k, the left-hand side of the equation remains increasing in $P^\star$ and decreasing in τ_k, and therefore the same rational applies as in the case $1-(1+\varphi)\psi > 0$.

C Model with perfect labor market

Let us consider that labor market is perfect and there is full employment.

The representative household chooses (C, L_s) and the supply of capital K_s to solve

$$\begin{aligned}&\max_{C,L_s,K_s,H}\int_t^\infty e^{-\rho(z-t)}u\left(C,1-T-L_s,h\right)dz\\ &s.t.\\ &\dot{K}_s=(1-\tau_k)rK_s+\mathit{\Pi}+(1-\tau_w)\tilde{w}L_s-C-H+S\\ &\dot{h}=\mathcal{G}(H,T)-\delta_h(P)h\\ &K_s(0)=K_{s0},\ h(0)=h_0\ given\end{aligned}$$

The current Hamiltonian is:

$$\begin{aligned}\mathcal{H}^{ho}&=u\left(C,1-T-L_s,h\right)\\ &\quad+\lambda_K\left[(1-\tau_k)rK_s+(1-\tau_w)\tilde{w}L_s-C-H+S\right]+\lambda_h\left[\mathcal{G}(H,T)-\delta_h(P)h\right]\end{aligned}$$

with transversality conditions such that:

$$\lim_{z\to\infty}\lambda_K K_s e^{\rho(t-z)}=\lim_{z\to\infty}\lambda_h h e^{\rho(t-z)}=0$$

First-order conditions are:[31]

$$\frac{\partial \mathcal{H}^{ho}}{\partial C} = 0 \qquad : \qquad u_1 - \lambda_K = 0 \tag{C.1}$$

$$\frac{\partial \mathcal{H}^{ho}}{\partial L_s} = 0 \qquad : \qquad -u_2 + (1-\tau_w)\tilde{w}\lambda_K = 0 \tag{C.2}$$

$$\frac{\partial \mathcal{H}^{ho}}{\partial H} = 0 \qquad : \qquad -\lambda_K + \mathcal{G}_1(H,T)\lambda_h = 0 \tag{C.3}$$

$$\frac{\partial \mathcal{H}^{ho}}{\partial T} = 0 \qquad : \qquad -u_2 + \mathcal{G}_2(H,T)\lambda_h = 0 \tag{C.4}$$

$$\dot{\lambda}_K - \rho\lambda_K = -\frac{\partial \mathcal{H}^{ho}}{\partial K_s} = -(1-\tau_k)r\lambda_K \tag{C.5}$$

$$\dot{\lambda}_h - \rho\lambda_h = -\frac{\partial \mathcal{H}^{ho}}{\partial h} = -u_3 + \delta_h(P)\lambda_h \tag{C.6}$$

(C.3) and (C.4) give

$$\lambda_h = u_1/\mathcal{G}_1(H,T) \qquad \text{and} \qquad \lambda_h = u_2/\mathcal{G}_2(H,T) \tag{C.7}$$

that is

$$\frac{\mathcal{G}_1(H,T)}{\mathcal{G}_2(H,T)} = \frac{u_1}{u_2} \tag{C.8}$$

and

$$\dot{\lambda}_h = -u_3 + [\rho + \delta_h(P)]\,\lambda_h \tag{C.9}$$

Rewriting first-order conditions, we get

$$\dot{C} = \frac{u_1}{u_{11}}\left[\rho - (1-\tau_k)r\right] \tag{C.10}$$

$$u_2 = (1-\tau_w)\tilde{w}u_1 \tag{C.11}$$

$$\lambda_h = u_1/\mathcal{G}_1(H,T) \tag{C.7}$$

$$\dot{\lambda}_h = -u_3 + [\rho + \delta_h(P)]\,\lambda_h \tag{C.9}$$

An individual firm chooses the demand for capital K_d and employment L_d to maximize its profit:

$$\begin{aligned}
&\max_{K_d, L_d} \Pi = (1-\tau_y)Y - \tilde{w}L_d - (r+\delta)K_d \\
&s.t. \\
&Y = \mathcal{F}\left(K_d, hL_d\right) \\
&K_d(0) = K_{d0} \ given
\end{aligned}$$

The first-order conditions are

$$(1-\tau_y)\mathcal{F}_L = \tilde{w} \tag{C.12}$$

$$(1-\tau_y)\mathcal{F}_K = r + \delta \tag{C.13}$$

[31]Recall that $\dfrac{\partial u\,(C,l,h)}{\partial i} = \dfrac{\partial u\,(C,l,h)}{\partial l}\dfrac{\partial l}{\partial i} = u_2 \times (-1)$, with $i = \{L_s, H\}$.

At the steady-state, $r = \rho$, then the physical capital stock per efficient labor at the steady-state equilibrium with perfect labor market, denoted $k^{f\star}$, is always equal to $k^\star$ given by equation (25) and then from equation (C.12)

$$w^{f\star} = (1-\alpha) f(\tau_k)^\alpha g(\tau_y) \tag{C.14}$$

Equation (C.11) with the expressions of u_1 and u_2 gives

$$C^{f\star} = \bar{\mathcal{A}}_1(\tau_y, \tau_k) h^{f\star} \left(T^{f\star} + L^{f\star}\right)^{-\varphi}$$
$$\text{where } \bar{\mathcal{A}}_1(\tau_y, \tau_k) \equiv \left(\frac{1-\mu_h}{\chi}\right)(1-\tau_w)(1-\alpha) f(\tau_k)^\alpha g(\tau_y) \tag{C.15}$$

which replaces (29).

Equation (A.24) remains unchanged except that now the steady-state stock of pollution is denoted by $P^{f\star}$ rather than $P^\star$, then equations (C.8) and (C.7) with the expressions of u_1 and u_2 gives

$$\mathcal{E}\left(P^{f\star}\right) \frac{\iota\,(1-\mu_h)}{\chi\psi} \left(T^{f\star} + L^{f\star}\right)^{-\varphi} = T^{f\star} \tag{C.16}$$

which replace (A.25). Using $\dot{K} = 0$ with public budget equilibium, it comes

$$C^{f\star} = \bar{\mathcal{A}}_2(\tau_y, \tau_k, P^{f\star}) h^{f\star} L^{f\star}$$
$$\text{where } \bar{\mathcal{A}}_2(\tau_y, \tau_k, P^{f\star}) \equiv \frac{\left[Z\left(\frac{1-\beta\tau_y}{1-\tau_y}\right) - \left(\delta + \beta\frac{\tau_k}{1-\tau_k}\rho\right) f(\tau_k)^{1-\alpha}\right] f(\tau_k)^\alpha g(\tau_y)}{1 + \mathcal{E}\left(P^{f\star}\right)} \tag{C.17}$$

which replaces (30). Therefore, from (C.15) and (C.17) with (C.16), let equation (A.34) becoming

$$L^{f\star} = \frac{\bar{\mathcal{A}}(\tau_y, \tau_k, P^{f\star})^{\frac{1}{1+\varphi}}}{\left[\frac{\mathcal{B}\mathcal{E}\left(P^{f\star}\right)}{\bar{\mathcal{A}}(\tau_y,\tau_k,P^{f\star})} + 1\right]^{\frac{\varphi}{1+\varphi}}} \tag{C.18}$$

$$T^{f\star} = \frac{\mathcal{B}\mathcal{E}\left(P^{f\star}\right)}{\left[\mathcal{B}\mathcal{E}\left(P^{f\star}\right) + \bar{\mathcal{A}}(\tau_y, \tau_k, P^{f\star})\right]^{\frac{\varphi}{1+\varphi}}} \tag{C.19}$$

where

$$\begin{cases} \bar{\mathcal{A}}(\tau_y, \tau_k, P^{f\star}) \equiv \frac{\bar{\mathcal{A}}_1(\tau_y,\tau_k)}{\bar{\mathcal{A}}_2(\tau_y,\tau_k,P^{f\star})} = \frac{(1-\alpha)Z\left(1+\mathcal{E}\left(P^{f\star}\right)\right)(1-\mu_h)}{\chi\left[Z\left(\frac{1-\beta\tau_y}{1-\tau_y}\right)-\left(\delta+\beta\frac{\tau_k}{1-\tau_k}\rho\right)f(\tau_k)^{1-\alpha}\right]} \\ \mathcal{B} \equiv \frac{(1-\mu_h)\iota}{\chi\psi} \end{cases}$$

Then, it comes

$$C^{f\star} = \left[\frac{\eta\bar{\mathcal{A}}_1(\tau_y, \tau_k)\mathcal{E}\left(P^{f\star}\right)^{\psi+\iota}\mathcal{B}^\iota}{\delta_h(P^{f\star})\left[\mathcal{B}\mathcal{E}\left(P^{f\star}\right) + \bar{\mathcal{A}}(\tau_y, \tau_k, P^{f\star})\right]^{\frac{\varphi(1+\iota)}{1+\varphi}}}\right]^{1/(1-\psi)} \tag{C.20}$$

and then

$$h^{f\star} = \left[\frac{\eta \bar{\mathcal{A}}_1(\tau_y, \tau_k)^{\psi} \mathcal{E}\left(P^{f\star}\right)^{\psi+\iota} \mathcal{B}^{\iota}}{\delta_h(P^{f\star}) \left[\mathcal{B}\mathcal{E}\left(P^{f\star}\right) + \bar{\mathcal{A}}(\tau_y, \tau_k, P^{f\star})\right]^{\frac{\varphi(\psi+\iota)}{1+\varphi}}} \right]^{1/(1-\psi)} \tag{C.21}$$

and finally

$$\begin{aligned} Y^{f\star} = \bar{\mathcal{Y}}(P^{f\star}, \tau_y, \tau_k) \equiv Z f(\tau_k)^{\alpha} g(\tau_y)^{\alpha} \left[\frac{\eta \mathcal{E}\left(P^{f\star}\right)^{\psi+\iota} \mathcal{B}^{\iota}}{\delta_h(P^{f\star})} \right]^{\frac{1}{1-\psi}} \\ \times \frac{\bar{\mathcal{A}}_1(\tau_y, \tau_k)^{\frac{1-\varphi\iota}{(1+\varphi)(1-\psi)}} \bar{\mathcal{A}}_2(\tau_y, \tau_k, P^{f\star})^{\frac{-\psi}{1-\psi}}}{\left[\frac{\mathcal{B}\mathcal{E}\left(P^{f\star}\right)}{\bar{\mathcal{A}}(\tau_y, \tau_k, P^{f\star})} + 1\right]^{\frac{\varphi(1+\iota)}{(1+\varphi)(1-\psi)}}} \end{aligned} \tag{C.22}$$

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