Fondazione Eni Enrico Mattei

NOTA DI LAVORO

36.2017

Environment, Health and Labor Market

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Economic Theory
Series Editor: Carlo Carraro

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Summary

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Keywords: Environmental Policy, Health, Labor Market, Search, Unemployment

JEL Classification: I1, J2, J64, Q58

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Environment, health and labor market

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June 29, 2017

Abstract

We re-examine the impact of environmental taxation on health and output, in the presence of labor market frictions. Our main findings are 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. We also demonstrate that rising abatement expenditures as a way of tightening the environmental policy would be better for health than increasing environmental tax in the presence of market labor imperfections.

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 according to which 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?

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It is well-established now that pollution and global warming have a detrimental impact on health, through both morbidity and mortality. Economic literature dealt with this empirical evidence to demonstrate that environmental policy, limiting pollution, could generate a double dividend by improving health (for the most recent contributions see Bretschger and Vinogradova, 2017; Palivos and Varvarigos, 2017; Klarl, 2016; Chen et al., 2015; Wang et al., 2015).

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 contribution deals with the role market labor, especially market labor imbalances, could play on the positive influence of the environmental policy on health.[1] Indeed, aforementioned 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. Furthermore, at the individual level the negative impact of job loss on individuals' health is becoming well-documented and therefore the expected positive effect of environmental policy on health could be overestimated.[2] Sullivan and von Wachter (2009) find 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,

[1]Note that some articles about environmental policy dealt with labor market, like the "*double dividend*" literature. However, few other articles account for labor market imperfections (for example Ono, 2008; Sanz and Schwartz, 2013; Hafstead and Williams III, 2016, amongst others).

[2]There is also a literature finding that at the aggregate level, mortality rate is procyclical and therefore recession is good for health because people 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. (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 vary according to whether mothers are hispanic, white, well-educated, less-educated,... For more details on the existing literature, see Suhrcke and Stuckler (2012); Currie et al. (2015); Modrek et al. (2017).

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.[3] 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[4] 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.

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. 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.[5] 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-

[3]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.

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

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

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:

1. A tighter environmental tax (on final output or physical capital) affects labor market equilibrium through different channels:
   - (a) it rises the tightness in the labor market
   - (b) it reduces the transmission of labor productivity gains towards wage
   - (c) it reduces the incentives to search for a job
   - (d) it increases the cost payed by a firm when it posts a vacancy job.
2. As a result, a tighter environmental tax increases the steady-state unemployment rate, whatever the source of pollution.
3. With respect to the perfect labor market economy, taking into account frictions on labor market and wage bargain:
   - (a) reduces the steady-state level of output, for a given environmental tax;
   - (b) reinforces the negative impact of a tighter environmental tax on final output.
4. 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" (detrimental) channels:
   - (a) through the incentives to search for a job,
   - (b) through the cost of a vacant job.

   These two effects lead to a reduction in health expenditures, *ceteris paribus* and therefore, with respect to the perfect labor market economy,
   - (a) they reduce the steady-state health status, for a given environmental tax,
   - (b) they reduce the positive impact of the environmental taxation on health.
5. Rising abatement expenditures as a way of tightening environmental protection would be better for health, because it does not introduce additional negative impacts arising from the labor market.

All these results mean that current articles studying the influence of environmental policy and health assuming perfect labor market overestimate the positive impact of environmental policy on health. They call for a quantitative investigation of the amplitude of the different effects highlighted in the literature.

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 conclude.

2 The basic framework

Let us consider the framework developed 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.[6] As a result, solving the representative household's maximization problem gives the agents' decisions.

The expected lifetime utility of the representative household is given by:

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

where h denotes health-status, C is consumption and l is the time used for leisure activities defined as:[7]

$$l = 1 - U - L_s$$

where U is the time used for search (unemployment), L_s is the time for work supplied by the household.

[6]See Shi and Wen (1999, p 460) for more details.
[7]Time index is dropped when there is no confusion

At each moment of time, some members of the household who are unemployed find a job, and another who are employed lose it (because a idiosyncratic choc destroys a constant part of existing work contracts on market labor).

Let denote by m, the rate at which unemployed agent finds a job and so 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, the employment evolves according to:

$$\dot{L}_s \equiv \frac{dL}{dz} = mU - \sigma L_s$$

Following Aisa and Pueyo (2004) and Pautrel (2012) among others, we assume that 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, denoted H.[8] The second one, negative, is mainly due to the detrimental impact of pollution on health. Therefore, the temporal evolution of the health status can be written as:

$$\dot{h} \equiv \frac{dh}{dz} = \eta H^{\psi} - \delta_h(P)h \tag{1}$$

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

Budget constraint of the households is given by:

$$\dot{K}_s \equiv \frac{dK_s}{dz} = (1-\tau_k)rK_s + \mathit{\Pi} + (1-\tau_w)\tilde{w}L_s - C - H + \tau_u\tilde{w}U + S \tag{2}$$

where $\tilde{w}$ is the wage expressed in efficiency terms, $(1-\tau_k)r$ is the after-tax interest rate and τ_u is the rate of subsidy to unemployment. $\mathit{\Pi}$ is the profit of the firm and τ_w is labor income tax. 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 chooses (C, L_s, U, H) and the supply of capital K_s to solve

$$\begin{array}{l}
\max\limits_{C,L_s,U,H,K_s} \int_t^{\infty} e^{-\rho(z-t)} u\left(C, 1-U-L_s, h\right) dz \\
s.t. \\
\dot{K}_s = (1-\tau_k)rK_s + \mathit{\Pi} + (1-\tau_w)\tilde{w}L_s - C - H + \tau_u\tilde{w}U + S \\
\dot{L}_s = mU - \sigma L_s \\
\dot{h} = \eta H^{\psi} - \delta_h(P)h \\
K_s(0) = K_{s0},\ L_s(0) = L_{s0},\ h(0) = h_0\ given
\end{array}$$

[8] In the appendix, 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.

First-order conditions give

$$\dot{C} = \frac{u_1}{u_{11}}\left[\rho - (1-\tau_k)r\right] \tag{$foc1$}$$

and

$$u_2 = m\lambda_L + \tau_u \tilde{w} u_1, \tag{$foc2$}$$

that is, the opportunity cost of search (the left-hand side) is equal to the marginal benefit of search (the right-hand side). Furthermore,

$$\lambda_L = \frac{(1-\tau_w)\tilde{w}u_1 - u_2 + \dot{\lambda}_L}{\rho + \sigma}, \tag{$foc3$}$$

that is, 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

$$\lambda_h = u_1 H^{1-\psi} / \left[\eta\psi\right] \tag{$foc4$}$$

$$\dot{\lambda}_h = -u_3 + \left[\rho + \delta_h(P)\right]\lambda_h \tag{$foc5$}$$

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:

$$Y = \mathcal{F}(K_d, hL_d) \equiv Z\left(K_d\right)^{\alpha}\left(hL_d\right)^{1-\alpha} \tag{3}$$

where K_d is the demand for physical capital, L_d is demand for labour. $Z > 0$ is a productivity parameter. h captures worker productivity, which is assumed to depend on health exclusively.[9] Because of frictions on market labor, the firm faces a linear cost of adjustment of the stock of labor, such that:

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

where q is the instantaneous probability to fill the vacant job.

An individual firm chooses the number of vacancy V, the demand for capital K_d and employment L_d in order to solve:

$$\begin{array}{l} \max\limits_{K_d, L_d, V} \int_t^{\infty} \mathit{\Pi} e^{(1-\tau_k)r(t-z)} dz \\ s.t. \\ \mathit{\Pi} = Y - \tilde{w}L_d - (r+\delta)K_d - (1-\tau_v)\tilde{\xi}_V V \\ \dot{L}_d = qV - \sigma L_d \\ Y = \mathcal{F}\left(K_d, hL_d,\right) \\ K_d(0) = K_{d0},\ L_d(0) = L_{d0}\ given \end{array}$$

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

where $\tilde{\xi}_V$ is the flow cost per vacancy in efficiency terms (that is $h \cdot \xi_V$), $0 < \delta < 1$ is the physical capital depreciation rate and τ_v is the per unit subvention to job posting. First-order conditions give

$$\mathcal{F}_K = r + \delta, \tag{$foc6$}$$

and

$$\mu_L q = (1 - \tau_v)\tilde{\xi}_V, \tag{$foc7$}$$

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

$$\mu_L = \frac{\mathcal{F}_L - \tilde{w} + \dot{\mu}_L}{(1 - \tau_k)r + \sigma}, \tag{$foc8$}$$

that is, 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 $(1 - \tau_k)r + \sigma$.

2.3 Matching and wage determination

On labor market, here 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 represent respectively the unemployed agents and aggregate job vacancies. We assume, as conventional, that the function $M(\cdot, \cdot)$ is a linearly homogenous function such that

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

where j is called 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:

$$m = m(\theta) = M_0 \theta^j \qquad\qquad q = q(\theta) = m(\theta)/\theta$$

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 $[(1 - \tau_w)\tilde{w}u_1 - u_2]\, dL$. An additional worker dL at the wage $\tilde{w}$ increases the firm's current-valued surplus by $[\mathcal{F}_L - \tilde{w}]\, dL$.[10] As a result, the negotiation consists in the following

[10] Note that $\dfrac{u_2}{(1 - \tau_w)u_1}$ can be interpreted like the agent's reservation wage.

program:

$$\max_{\tilde{w}} \left[\mathcal{F}_L - \tilde{w}\right]^{1-\phi} \left[(1-\tau_w)u_1\tilde{w} - u_2\right]^{\phi}$$

where $\phi \in (0,1)$ is the worker's bargaining power. Solving the Nash problem yields:[11]

$$\tilde{w} = \phi\mathcal{F}_L + (1-\phi)\frac{u_2}{(1-\tau_w)u_1} \tag{4}$$

2.4 Government and ecology

Ecology is captured by the stock of pollution P which rises with the flow of pollution emission E and is reduced by abatement activities denoted by A, such that the law of motion of the stock of pollution is

$$\dot{P} = \Omega\left(E, A\right) - \gamma P,$$

where $\gamma > 0$ is the nature regeneration rate, and $\Omega\left(E, A\right)$ is the net flow of pollution (with $\Omega_1 > 0$ and $\Omega_2 < 0$). For simplicity we assume that $\Omega(E, A) \equiv E - A$.[12]

Here, we suppose that physical capital is the source of pollution.[13] Then the flow of polluting emissions is defined as $E = \pi_k K$ where $\pi_k \geq 0$ is the polluting capacity of physical capital stock.

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 (which used forgone output), denoted by A:

$$\beta\tau_k r K = A \tag{5}$$

and therefore

$$\dot{P} = \left(\pi_k - \beta\tau_k r\right)K - \gamma P \tag{6}$$

The remaining of the environmental tax revenue is used with the labor tax revenue to fund unemployment benefits, vacancy subsidies and lump-sum transfers:

$$(1-\beta)\tau_k r K + \tau_w \tilde{w} L = \tau_u \tilde{w} U + S + \tau_v \tilde{\xi}_V V \tag{7}$$

[11] In a standard neoclassical model, $\tilde{w} = \mathcal{F}_L = \dfrac{u_2}{(1-\tau_w)u_1}$.

[12] Assuming that $\Omega(E, A) \equiv E/A$ would not modify the qualitative results of the model. Proof upon request.

[13] In the appendix A page 18, we develop a general version of this model in which we take into account both physical capital and final output as sources of pollution. We demonstrate in appendix A.2 page 23 that results are not qualitatively modified when output is assumed to be the source of pollution instead of physical capital.

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.

We assume that utility function 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):[14]

$$u(C, 1-U-L, h) \equiv \log\left(C^{1-\mu_h} h^{\mu_h}\right) - \chi \frac{(U+L)^{1+\varphi}}{1+\varphi}, \qquad 0 < \sigma_h < 1$$

with $\chi > 0$, $\mu_h \in]0,1[$ the weight of consumption in utility, $1/\sigma_h$ is the intertempral elasticity of substitution. Parameter $\varphi > 0$ captures Frisch elasticity of labor supply.

At the steady-state, $\dot{P} = 0$, therefore from (6):

$$P^\star = \frac{1}{\gamma}\left(\pi_k - \beta\tau_k r^\star\right) K^\star \tag{8}$$

Because at the steady-state equilibrium, $\dot{\lambda}_h = 0$, from equations (*foc*4) and (*foc*5), we can express the expenditures in health care as a proportion $\mathcal{E}(P^\star) \in]0,1[$ of the steady-state consumption level $C^\star$:

$$H^\star = \mathcal{E}(P^\star)\, C^\star \qquad \text{with } \mathcal{E}(P^\star) \equiv \frac{\psi\delta_h(P^\star)}{\rho + \delta_h(P^\star)}\left(\frac{\mu_h}{1-\mu_h}\right) \tag{9}$$

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

Because at the steady-state equilibrium, $\dot{C} = 0$, it comes from (*foc*1), $(1-\tau_k)r = \rho$, and therefore equation (*foc*6) gives physical capital per efficient unit of labor, $k \equiv K/(hL)$, as a function of the environmental tax:

$$k^\star = b(\tau_k) \qquad \text{where} \qquad b(\tau_k) \equiv \left[\frac{Z\alpha}{\dfrac{\rho}{1-\tau_k} + \delta}\right]^{1/(1-\alpha)} \tag{10}$$

Because at the steady-state equilibrium, $\dot{\lambda}_L = 0$, we obtain from (*foc*2) and (*foc*3):

$$u_2^\star(\rho + \sigma + m(\theta^\star)) = u_1^\star \tilde{w}^\star\left[m(\theta^\star)(1-\tau_w) + (\sigma+\rho)\tau_u\right] \tag{11}$$

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

Putting this expression in (4) gives the wage rate expressed in efficient units:

$$\tilde{w}^\star = \Phi(\theta^\star)\mathcal{F}_L^\star \qquad \text{where } \Phi(\theta^\star) \equiv \frac{\phi(\rho+\sigma+m(\theta^\star))(1-\tau_w)}{(\rho+\sigma+m(\theta^\star)\phi)(1-\tau_w)-(1-\phi)(\sigma+\rho)\tau_u} < 1 \tag{12}$$

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).

Because $\dot{\mu_L} = 0$, from ($foc7$), ($foc8$) and (12), the tightness of labor market at the steady-state $\theta^\star$ is given by the following equation

$$(1-\alpha)Zb(\tau_k)^\alpha = \frac{\theta^\star\,(\rho+\sigma)\,(1-\tau_v)\xi_V}{m(\theta^\star)\,[1-\Phi(\theta^\star)]} \tag{13}$$

Proposition 1. *In the presence of frictions on labor market and wage bargaining, a tighter environmental tax increases the tightness in labor market at steady-state:*

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

Proof. From equation (13). □

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.

Corollary 1. *In the presence of frictions on labor market and wage bargaining, a tighter environmental tax reduces the transmission of labor productivity gains to wage: $\Phi(\theta^\star)$ with $d\Phi(\theta^\star)/d\tau_k < 0$.*

Proof. From equation (12). □

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

$$U^\star = \frac{\sigma}{m(\theta^\star)}L^\star \tag{14}$$

Corollary 2. *Taking into account frictions on labor market and wage bargaining, a tighter environmental tax rises the steady-state unemployment rate $(U^\star + L^\star)/L^\star$.*

Proof. Straightforward from equation (14) and Proposition 1. $\square$

Replacing by the expressions of u_1 and u_2 in equation (11) and using (12) and (14), we can re-express the equality between the opportunity cost of search and the marginal benefit of search, obtaining a relationship between $C^\star$ and $L^\star$:

$$C^\star = (1-\alpha) Z b(\tau_k)^\alpha \left(\frac{1-\mu_h}{\chi}\right) \Lambda_1(\theta^\star) L^{\star -\varphi} h^\star$$
$$\text{where } \Lambda_1(\theta^\star) \equiv \Phi(\theta^\star) \frac{(1-\tau_w)m(\theta^\star) + (\sigma+\rho)\tau_u}{\sigma+\rho+m(\theta^\star)} \left(\frac{\sigma}{m(\theta^\star)}+1\right)^{-\varphi} \tag{15}$$

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

Corollary 3. *Taking into account frictions on labor market and wage bargaining, a tighter environmental tax 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.*

Proof. Straightforward from the expression of $\Lambda_1(\theta^\star)$ in equation (15) and Proposition 1. $\square$

$\Lambda_1(\theta^\star)$ 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 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 $\frac{(1-\tau_w)m(\theta^\star)+(\sigma+\rho)\tau_u}{\sigma+\rho+m(\theta^\star)}$. 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 $\left(\frac{\sigma}{m(\theta^\star)}+1\right)^{-\varphi}$.

Because $\dot{K} = 0$, using (5), (14) and (2), we can define a second relationship between $C^\star$ and $L^\star$:

$$C^\star = \frac{\left[Z - \left(\delta + \beta\frac{\tau_k}{1-\tau_k}\rho\right) b(\tau_k)^{1-\alpha}\right] b(\tau_k)^\alpha - \Lambda_2(\theta^\star)}{1+\mathcal{E}(P^\star)} h^\star L^\star$$
$$\text{where } \Lambda_2(\theta^\star) \equiv \frac{\sigma\theta^\star}{m(\theta^\star)}(1-\tau_v)\xi_V \tag{16}$$

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

Corollary 4. *Taking into account frictions on labor market and wage bargaining, a tighter environmental tax 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. Straightforward from the expression of $\Lambda_2(\theta^\star)$ in equation (16) and Proposition 1. □

Equation (16) 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.

Finally, using (15), (16) and previous results, we obtain[15] the steady-state amount of labor employed in production :

$$L^\star = \mathcal{L}(P^\star, \tau_k) \equiv \left[\frac{(1+\mathcal{E}(P^\star))(1-\alpha)Z\left(\frac{1-\mu_h}{\chi}\right)\Lambda_1(\Theta(\tau_k))}{Z - \left(\delta + \beta\frac{\tau_k}{1-\tau_k}\rho\right) b(\tau_k)^{1-\alpha} - \frac{\Lambda_2(\Theta(\tau_k))}{b(\tau_k)^\alpha}} \right]^{\frac{1}{1+\varphi}}, \quad (17)$$

the steay-state level of consumption:

$$\begin{aligned} C^\star = {} & \left[\frac{\eta\mathcal{E}(P^\star)^{\psi+\iota}}{\delta_h(P^\star)}\right]^{\frac{1}{1+\varphi}} \left\{ [1+\mathcal{E}(P^\star)]^{-\varphi}(1-\alpha)Zb(\tau_k)^\alpha \left(\frac{1-\mu_h}{\chi}\right)\Lambda_1(\Theta(\tau_k)) \right. \\ & \left. \times \left[\left(Z - \left(\delta + \beta\frac{\tau_k}{1-\tau_k}\rho\right) b(\tau_k)^{1-\alpha}\right) b(\tau_k)^\alpha - \Lambda_2(\theta^\star)\right]^\varphi \right\}^{\frac{1}{(1-\psi)(1+\varphi)}} \quad (18) \end{aligned}$$

the health-status of each individual:

$$\begin{aligned} h^\star = {} & \left(\frac{\eta\mathcal{E}(P^\star)^\psi}{\delta_h(P^\star)}\right)^{\frac{1}{1-\psi}} (1+\mathcal{E}(P^\star))^{\frac{-\psi\varphi}{(1-\psi)(1+\varphi)}} \quad (19) \\ & \times \left\{ \Lambda_1(\theta^\star) \left[\left(Z - \left(\delta + \beta\frac{\tau_k}{1-\tau_k}\rho\right) b(\tau_k)^{1-\alpha}\right) b(\tau_k)^\alpha - \Lambda_2(\Theta(\tau_k))\right]^\varphi \right\}^{\frac{\psi}{(1-\psi)(1+\varphi)}}, \end{aligned}$$

and the expression of final output:

$$\begin{aligned} Y^\star = \mathcal{Y}(P^\star, \tau_k) \equiv {} & Z\left[b(\tau_k)^\alpha \frac{\eta\mathcal{E}(P^\star)^\psi}{\delta_h(P^\star)}\right]^{\frac{1}{1-\psi}} \left[(1-\alpha)Z\left(\frac{1-\mu_h}{\chi}\right)\Lambda_1(\Theta(\tau_k))\right]^{\frac{1}{(1-\psi)(1+\varphi)}} \quad (20) \\ & \times \left[\frac{(1+\mathcal{E}(P^\star))}{Z - \left(\delta + \beta\frac{\tau_k}{1-\tau_k}\rho\right) b(\tau_k)^{1-\alpha} - \frac{\Lambda_2(\Theta(\tau_k))}{b(\tau_k)^\alpha}} \right]^{\frac{1-\psi(1+\varphi)}{(1-\psi)(1+\varphi)}} \end{aligned}$$

[15] Demonstration in appendix A page 21.

where $\Theta'(\tau_k) < 0$, $\Lambda_1(\Theta(\tau_k))$ and $\Lambda_2(\Theta(\tau_k))$ are respectively defined in equation (15) and (16). Finally, using (8) and (20), the steady-state stock of pollution is given by the following implicit function:

$$P^\star = \left(\pi_k - \beta \frac{\tau_k \rho}{1-\tau_k}\right) b(\tau_k)^{1-\alpha} \mathcal{Y}(P^\star, \tau_k)/Z \tag{21}$$

Proposition 2. *The net flow of pollution at steady-state is defined as:*

$$P^\star = \mathcal{P}(\tau_k) \qquad \textit{with} \qquad \mathcal{P}'(\tau_k) < 0 \tag{22}$$

Proof. See appendix B page 25. □

Furthermore, it comes

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

1. *reduces the steady-state level of output, for a given environmental tax;*
2. *reinforces the negative impact of a tighter environmental tax on final output.*

Proof. The influence of imperfections on labor market is captured by $\Lambda_1(\Theta(\tau_k))$ and $\Lambda_2(\Theta(\tau_k))$ in equation (20). $0 < \Lambda_1(\Theta(\tau_k)) < 1$ from equation (15) and $\Lambda_2(\Theta(\tau_k)) > 0$ from equation (16), and from appendix B page 25, we know that $P^\star$ increases in $\Lambda_1(\Theta(\tau_k))$ and $\Lambda_2(\Theta(\tau_k))$. Then comparing $Y^\star$ with the steady-state level of output in the presence of free labor market $Y^{f\star}$ (given by equation C.22 in appendix C page 28), it is straightforward that $Y^\star < Y^{f\star}$.

Furthermore, from Corollaries 3 and 4, $\Lambda_1(\Theta(\tau_k))$ and $\Lambda_2(\Theta(\tau_k))$ both decrease in τ_k, adding two further negative impacts of the environmental tax on steady-state output. □

According to Proposition 3, taking into account frictions on labor market and wage bargaining tends to rise the negative impact of the environmental tax on both labor supply, consumption and final output (see respectively equations 17, 18 and 20). As a consequence, a tighter environmental tax will not only worsen unemployment in the economy, it will hurt more strongly all the economy through the impact of the tightening of the labor market.

In the same way, not taking into account imperfections on labor market leads to overestimate the positive impact of the environmental tax on health status, as stated in the following proposition.

Proposition 4.

1. *Taking into account frictions on labor market and wage bargain introduces two "new" (detrimental) channels:*

   (a) *the "incentives to search for a job" effect (captured by $\Lambda_1(\Theta(\tau_k))$).*

(b) *the "vacancy cost" effect (captured by $\Lambda_2(\Theta(\tau_k))$).*

2. *With respect to the perfect labor market economy, these two new channels:*

   (a) *reduce the steady-state health status, for a given environmental tax,*

   (b) *reduce the positive impact of the environmental taxation on health.*

Proof. Straightforward from equation (19) and corollaries 3 and 4. $\square$

There are 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 reduction*" effect is captured by the term $\left(\frac{\eta\mathcal{E}(P^\star)^\psi}{\delta_h(P^\star)}\right)^{\frac{1}{1-\psi}}\left(1+\varepsilon(P^\star)\right)^{\frac{-\psi\varphi}{(1-\psi)(1+\varphi)}}$ in equation (19). 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 $\left[Z-\left(\delta+\beta\frac{\tau_k}{1-\tau_k}\rho\right)b(\tau_k)^{1-\alpha}\right]b(\tau_k)^\alpha$ in equation (19). Third, the increase in environmental tax rises the tightness on market labor and the unemployment rate. As noted in Corollary 3 page 12, 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 $\Lambda_1(\Theta(\tau_k))$ in equation (19). Fourth, as noted in Corollary 4, a tighter environmental tax by reducing the probability of matching rises the cost of vacancy and as the result 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 $\Lambda_2(\Theta(\tau_k))$ in equation (19). 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.

Propositions 3 and 4 do not mean that the two new channels of transmission of the environmental tax introduced by imperfections on labor market leads to a global negative impact of environmental regulation on output and health. Further investigations are required to evaluate if these two negative effects offset the health dividend found in the presence of prefect market labor.[16]

[16] This is the subject to a current work in progress.

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. Because in our model, we allow the revenue of the environmental tax to not be fully used for funding abatement (through parameter β in equation (5) page 9), a way to capture the role played by abatement expenditures as environmental policy is to investigate how β affects the economy and the labor market.

We derive the following proposition from previous exposition of the model:

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 (19), (20) and (22). □

It comes the interesting following insight:

Corollary 5. *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.*

Proof. Directly from Proposition 5.1. □

5 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 model with pollution, endogenous health-status and imperfections on labor market.

The contribution of the article is manyfold. Especially, it shows that a higher environmental tax increases the labor market tightness and therefore the unemployment rate in the long run. It also demonstrates that market labor imperfections introduce new channels of transmission of environmental policy on health which reduce the expected positive effect of less pollution on health. Our model is coherent with the empirical evidence according to, at firm-level, layoffs (captured here by a rise in unemployment) are detrimental for health. Finally, it demonstrates that increasing abatement expenditures as a way of tightening the environmental policy would be better for health than increasing environmental tax in the presence of market labor imperfections.

Further investigations are required, especially to evaluate quantitatively the two negative effects of environmental tax on health arising from labor market imperfections and the global effect of the environmental tax on health. Furthermore, our modeling could be enriched by introducing an explicit abatement sector (like in Hafstead and Williams III, 2016) to investigate how our results are modified.

APPENDIX

A Model resolution

Here, we solve the model taking into account both τ_y and τ_k in the same framework.

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

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

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:

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

First-order conditions are:[17]

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

$$\frac{\partial \mathcal{H}^{ho}}{\partial U} = 0 \qquad : \qquad \tau_u \tilde{w} \lambda_K - u_2 + m\lambda_L = 0 \tag{A.2}$$

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

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

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

$$\dot{\lambda}_L - \rho\lambda_L = -\frac{\partial \mathcal{H}^{ho}}{\partial L_s} = u_2 - (1-\tau_w)\tilde{w}\lambda_K + \sigma\lambda_L \tag{A.6}$$

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

$$\dot{\lambda}_h - \rho\lambda_h = -\frac{\partial \mathcal{H}^{ho}}{\partial h} = -u_3 + \delta_h(P)\lambda_h \tag{A.7}$$

Rewriting first-order conditions, we get

$$\dot{C} = \frac{u_1}{u_{11}}\left[\rho - (1-\tau_k)r\right] \tag{A.8}$$

$$m\lambda_L = u_2 - \tau_u \tilde{w} u_1 \tag{A.9}$$

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).

$$\lambda_L = \frac{(1-\tau_w)\tilde{w}u_1 - u_2 + \dot{\lambda}_L}{\rho + \sigma} \tag{A.10}$$

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,

$$\lambda_h = u_1/\mathcal{G}_1(H,T) \qquad \text{and} \qquad \lambda_h = u_2/\mathcal{G}_2(H,T) \tag{A.11}$$

that is

$$\frac{\mathcal{G}_1(H,T)}{\mathcal{G}_2(H,T)} = \frac{u_1}{u_2} \tag{A.12}$$

$$\dot{\lambda}_h = -u_3 + \left[\rho + \delta_h(P)\right]\lambda_h \tag{A.13}$$

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

$$\frac{\partial \mathcal{H}^f}{\partial V} = 0 \qquad : \qquad (1-\tau_v)\tilde{\xi}_V = \mu_L q \tag{A.14}$$

$$\frac{\partial \mathcal{H}^f}{\partial K_d} = 0 \qquad : \qquad (1-\tau_y)\mathcal{F}_K = r + \delta \tag{A.15}$$

$$\dot{\mu}_L - (1-\tau_k) r\mu_L = -\frac{\partial \mathcal{H}^f}{\partial L_d} = -\left[(1-\tau_y)\mathcal{F}_L - \tilde{w}\right] + \sigma\mu_L \tag{A.16}$$

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

$$(1-\tau_y)\mathcal{F}_K = r + \delta \tag{A.17}$$

$$\mu_L q = (1-\tau_v)\tilde{\xi}_V \tag{A.18}$$

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

$$\mu_L = \frac{(1-\tau_y)\mathcal{F}_L - \tilde{w} + \dot{\mu}_L}{(1-\tau_k)r + \sigma} \tag{A.19}$$

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 (which used forgone output), denoted by A: $\beta\left(\tau_y Y + \tau_k r K\right) = A$. The remaining of the environmental tax revenue is used with the labor tax revenue to fund unemployment benefits, vacancy subsidies and lump-sum transfers:

$$(1-\beta)\left(\tau_y Y + \tau_k r K\right) + \tau_w \tilde{w} L = \tau_u \tilde{w} U + S + \tau_v \tilde{\xi}_V V \tag{A.20}$$

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.1), C, H, T, U, L, V, K, Y are constant.

Utility function is:

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

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 (6):

$$P^\star = \frac{1}{\gamma}\left[\left(\pi_y - \beta\tau_y\right) Y^\star + \left(\pi_k - \beta\tau_k r^\star\right) K^\star\right] \tag{A.21}$$

Furthermore, we can define

$$\mathcal{G}(H,T) \equiv \begin{cases} \eta \left[\psi H^{\sigma_{\mathcal{G}}} + \iota T^{\sigma_{\mathcal{G}}}\right]^{1/\sigma_{\mathcal{G}}}, & \sigma_{\mathcal{G}} \in]-\infty, 0[\cup]0,1] \\ \eta H^{\psi} T^{\iota}, & \sigma_{\mathcal{G}} = 0 \end{cases}$$

therefore

$$\mathcal{G}_1(H,T) = \eta\psi H^{\sigma_{\mathcal{G}}-1} \left[\psi H^{\sigma_{\mathcal{G}}} + \iota T^{\sigma_{\mathcal{G}}}\right]^{1/\sigma_{\mathcal{G}}-1}$$
$$\mathcal{G}_2(H,T) = \eta\iota T^{\sigma_{\mathcal{G}}-1} \left[\psi H^{\sigma_{\mathcal{G}}} + \iota T^{\sigma_{\mathcal{G}}}\right]^{1/\sigma_{\mathcal{G}}-1}$$

Then from (A.12) $\dfrac{(1-\mu_h)\,\chi\,(T+U+L)^{\varphi}}{C} = \dfrac{\psi}{\iota}\left(\dfrac{H}{T}\right)^{\sigma_{\mathcal{G}}-1}$ that is

$$H = \left[\frac{\psi C}{\iota\,(1-\mu_h)\,\chi\,(T+U+L)^{\varphi}}\right]^{1/(1-\sigma_{\mathcal{G}})} T \tag{A.22}$$

Because $\dot{\lambda}_h = 0$, from equations (A.11) and (A.13), 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 :

$$H^\star = \mathcal{E}(P^\star)C^\star \qquad \text{with } \mathcal{E}(P^\star) \equiv \frac{\psi\delta_h(P^\star)}{\rho+\delta_h(P^\star)}\left(\frac{\mu_h}{1-\mu_h}\right) \tag{A.23}$$

To keep the model tractable, we assume in this version that health-care expenditures et health-enhancing time are unitary substitutes, that is $\sigma_{\mathcal{G}} = 0$. As a consequence, equation (A.23) gives the implicit expression of $T^\star$:

$$\mathcal{E}(P^\star)\frac{\iota\,(1-\mu_h)}{\chi\psi}\,(T^\star + U^\star + L^\star)^{-\varphi} = T^\star \tag{A.24}$$

Because $\dot{C} = 0$, it comes from (A.8), $(1-\tau_k)r = \rho$ and therefore equation (A.15) 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:

$$k^\star = b(\tau_k)g(\tau_y) \tag{A.25}$$

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

Because $\dot{\lambda}_L = 0$, we obtain from (A.9) and (A.10):

$$u_2^\star(\rho+\sigma+m(\theta^\star)) = u_1^\star\tilde{w}^\star\left[m(\theta^\star)(1-\tau_w) + (\sigma+\rho)\tau_u\right] \tag{A.26}$$

Putting this expression in (4) gives:

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

$$(A.27)$$

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

Recalling that a variable $\tilde{x}$ expressed in efficiency units can by written as $h \cdot x$, and using (A.9), (A.27) and (A.25), we can express the wage rate as:

$$w^\star = \Phi(\theta^\star)(1-\alpha)Zb(\tau_k)^\alpha g(\tau_y) \tag{A.28}$$

Because $\dot{\mu_L} = 0$, from (A.18), (A.19) and (A.28):

$$(1-\alpha)Zb(\tau_k)^\alpha g(\tau_y) = \frac{\theta^\star\,(\rho+\sigma)\,(1-\tau_v)\xi_V}{m(\theta^\star)\,[1-\Phi(\theta^\star)]} \tag{A.29}$$

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

$$U^\star = \frac{\sigma}{m(\theta^\star)} L^\star \tag{A.30}$$

Replacing by the expressions of u_1 and u_2 in equation (A.26) and using (A.27) and (A.30), we obtain

$$\begin{aligned} C^\star &= \mathcal{A}_1(\theta^\star, \tau_y, \tau_k) h^\star \left(\left(\frac{\sigma}{m(\theta^\star)} + 1 \right)^{-1} T^\star + L^\star \right)^{-\varphi} \\ \text{where } \mathcal{A}_1(\theta^\star, \tau_y, \tau_k) &\equiv (1-\alpha)Zb(\tau_k)^\alpha g(\tau_y) \left(\frac{1-\mu_h}{\chi} \right) \Lambda_1(\theta^\star) \\ \text{and } \Lambda_1(\theta^\star) &\equiv \Phi(\theta^\star) \frac{(1-\tau_w)m(\theta^\star) + (\sigma+\rho)\tau_u}{\sigma+\rho+m(\theta^\star)} \left(\frac{\sigma}{m(\theta^\star)} + 1 \right)^{-\varphi} \end{aligned} \tag{A.31}$$

Because $\dot{K} = 0$, using (A.20), (A.30) and (2) enables us to define a second relation between $C^\star$ and $L^\star$:

$$\begin{aligned} C^\star &= \mathcal{A}_2(\theta^\star, \tau_y, \tau_k, P^\star) h^\star L^\star \\ \text{where } \mathcal{A}_2(\theta^\star, \tau_y, \tau_k, P^\star) &\equiv \frac{\left[Z\left(\frac{1-\beta\tau_y}{1-\tau_y}\right) - \left(\delta + \beta\frac{\tau_k}{1-\tau_k}\rho\right) b(\tau_k)^{1-\alpha} \right] b(\tau_k)^\alpha g(\tau_y) - \Lambda_2(\theta^\star)}{1+\mathcal{E}(P^\star)} \\ \text{and } \Lambda_2(\theta^\star) &\equiv \frac{\sigma\theta^\star}{m(\theta^\star)}(1-\tau_v)\xi_V \end{aligned} \tag{A.32}$$

Therefore, (A.31) and (A.32), with (A.24), give:

$$L^\star = \frac{\mathcal{A}(\theta^\star, \tau_y, \tau_k, P^\star)}{[\mathcal{B}\mathcal{E}(P^\star) + \mathcal{A}(\theta^\star, \tau_y, \tau_k, P^\star)]^{\frac{\varphi}{1+\varphi}}} \tag{A.33}$$

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

where

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

Because $\dot{h} = 0$ at the steady-state, equation (1) gives $h^\star = \eta \dfrac{\mathcal{E}(P^\star)^\psi C^{\star\psi} T^{\star\iota}}{\delta_h(P^\star)}$. Then, from (A.32) 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

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

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

$$Y^\star = \mathcal{Y}(P^\star, \tau_y, \tau_k) \equiv Zb(\tau_k)^\alpha g(\tau_y)^\alpha \left[\frac{\eta\mathcal{E}(P^\star)^{\psi+\iota}\mathcal{B}^\iota}{\delta_h(P^\star)}\right]^{\frac{1}{1-\psi}} \times \frac{\mathcal{A}(\theta^\star, \tau_y, \tau_k, P^\star)\mathcal{A}_1(\theta^\star, \tau_y, \tau_k)^{\frac{\psi}{1-\psi}}}{[\mathcal{B}\mathcal{E}(P^\star) + \mathcal{A}(\theta^\star, \tau_y, \tau_k, P^\star)]^{\frac{\varphi(1+\iota)}{(1+\varphi)(1-\psi)}}} \quad \text{(A.35)}$$

And $P^\star$ is defined by:

$$P^\star - \left[\pi_y - \beta\tau_y + \left(\pi_k - \beta\frac{\tau_k\rho}{1-\tau_k}\right) b(\tau_k)^{1-\alpha} g(\tau_y)^{1-\alpha}\right] \mathcal{Y}(P^\star, \tau_y, \tau_k) = 0 \quad \text{(A.36)}$$

Therefore, the system of equations (A.35) and (A.36) define $Y^\star$ and $P^\star$ as a function of τ_y and τ_k.

A.2 The special case where final output as a source of pollution

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

Therefore (10) becomes

$$k^\star = \mathcal{B}_1 g(\tau_y) \quad \text{(10y)}$$

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

Government is also modified because in this model the revenue of the environmental tax is $\tau_y Y^\star$. Therefore, budget equilibrium leads to $A = \beta \tau_y Y^\star$, and because emissions equal $K^\star$, equation (8) becomes

$$P^\star = [\pi_y - \beta \tau_y] \, Y^\star \tag{8y}$$

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

As a result, $\theta^\star$ previously defined by equation (13) is defined by:

$$(1-\alpha) Z \mathcal{B}_1^\alpha g(\tau_y) = \frac{\theta^\star \, (\rho+\sigma)\, (1-\tau_v)\xi_V}{m(\theta^\star)\, [1 - \Phi(\theta^\star)]} \tag{13y}$$

Therefore, 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 (9) remains the same, then it comes

$$L^\star = \left[\frac{(1-\alpha) Z \,(1 + \mathcal{E}(P^\star))\,(1-\mu_h) \Lambda_1\left(\Theta^y(\tau_y)\right)}{\chi\left[Z\left(\frac{1-\beta\tau_y}{1-\tau_y}\right) - \delta \mathcal{B}_1^{1-\alpha} - \frac{\Lambda_2(\Theta^y(\tau_y))}{\mathcal{B}_1^\alpha g(\tau_y)}\right]}\right]^{\frac{1}{1+\varphi}} \tag{17y}$$

This additional influence comes from the fact that taxing physical capital income reduces the wage interest rate ratio and therefore it incites agents to supply more labor everything being equal.

$$\begin{aligned} C^\star = {} & \left[\frac{\eta \mathcal{E}(P^\star)^{\psi+\iota}}{\delta_h(P^\star)}\right]^{\frac{1}{1+\varphi}} [1 + \mathcal{E}(P^\star)]^{\frac{-\varphi}{(1-\psi)(1+\varphi)}} \left\{(1-\alpha) Z \mathcal{B}_1^\alpha g(\tau_y) \left(\frac{1-\mu_h}{\chi}\right) \Lambda_1\left(\Theta^y(\tau_y)\right)\right. \\ & \left. \times \left[\left[Z\left(\frac{1-\beta\tau_y}{1-\tau_y}\right) - \delta \mathcal{B}_1^{1-\alpha}\right] \mathcal{B}_1^\alpha g(\tau_y) - \Lambda_2\left(\Theta^y(\tau_y)\right)\right]^\varphi \right\}^{\frac{1}{(1-\psi)(1+\varphi)}} \end{aligned} \tag{18y}$$

and

$$\begin{aligned} h^\star = {} & \left[\frac{\eta \mathcal{E}(P^\star)^{\psi+\iota}}{\delta_h(P^\star)}\right]^{\frac{1}{1+\varphi}} [1 + \mathcal{E}(P^\star)]^{\frac{-\varphi\psi}{(1-\psi)(1+\varphi)}} \left\{(1-\alpha) Z \mathcal{B}_1^\alpha g(\tau_y) \left(\frac{1-\mu_h}{\chi}\right) \Lambda_1\left(\Theta^y(\tau_y)\right)\right. \\ & \left. \times \left[\left(Z\left(\frac{1-\beta\tau_y}{1-\tau_y}\right) - \delta \mathcal{B}_1^{1-\alpha}\right) \mathcal{B}_1^\alpha g(\tau_y) - \Lambda_2\left(\Theta^y(\tau_y)\right)\right]^\varphi \right\}^{\frac{\psi}{(1-\psi)(1+\varphi)}} \end{aligned} \tag{19y}$$

and

$$Y^\star = \tilde{\mathcal{Y}}(P^\star, \tau_y) \equiv Z \left[g(\tau_y)^{\alpha(1-\psi)+\psi} \frac{\eta \mathcal{E}(P^\star)^\psi}{\delta_h(P^\star)} \right]^{\frac{1}{1-\psi}} \left[(1-\alpha) Z \left(\frac{1-\mu_h}{\chi} \right) \Lambda_1 \left(\Theta^y(\tau_y) \right) \right]^{\frac{1}{(1-\psi)(1+\varphi)}}$$
$$\times \left[\frac{(1+\mathcal{E}(P^\star))}{Z\left(\frac{1-\beta\tau_y}{1-\tau_y}\right) - \delta \mathcal{B}_1^{1-\alpha} - \frac{\Lambda_2(\Theta^y(\tau_y))}{\mathcal{B}_1^\alpha g(\tau_y)}} \right]^{\frac{1-\psi(1+\varphi)}{(1-\psi)(1+\varphi)}} \qquad (20y)$$

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

$$P^\star = (\pi_y - \beta \tau_y)\, \tilde{\mathcal{Y}}(P^\star, \tau_y) \qquad (21y)$$

Following the same rationale than in appendix B page 25, it comes that the net flow of pollution at steady-state is defined as:

$$P^\star = \tilde{\mathcal{P}}(\tau_y) \qquad \text{with} \qquad \mathcal{P}'(\tau_y) < 0 \qquad (22y)$$

It is straightforward from equations (18y), (19y), (20y) and (22y) that the influences of labor market imperfections on the economy are qualitatively similar when the source of pollution is final output rather than physical capital. We expect that the size of the negative effects could be greater because in the case of pollution from final output, environmental tax is upon physical capital and labor.

B Proof of Proposition 2

Using (8) and (20), $P^\star$ is the solution of

$$P^\star - \left(\pi_k - \beta \frac{\tau_k \rho}{1-\tau_k} \right) b(\tau_k)^{1-\alpha} \mathcal{Y}(P^\star, \tau_k)/Z = 0 \qquad (21)$$

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 (21) can be written as (using 20):

$$P^{\star(1+\varphi)(1-\psi)} \left[\frac{(1+\mathcal{E}(P^\star))}{Z - \left(\delta + \beta \frac{\tau_k}{1-\tau_k}\rho\right) b(\tau_k)^{1-\alpha} - \frac{\Lambda_2(\Theta(\tau_k))}{b(\tau_k)^\alpha}} \right]^{(1+\varphi)\psi - 1}$$
$$-(1-\alpha)\left(\frac{1-\mu_h}{\chi}\right) \left(Z b(\tau_k)^\alpha \frac{\eta \mathcal{E}(P^\star)^\psi}{\delta_h(P^\star)} \right)^{1+\varphi} \Lambda_1\left(\Theta(\tau_k)\right) = 0$$

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

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

The current Hamiltonian is:

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

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:[18]

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

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

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

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

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

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

(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

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

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

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

Rewriting first-order conditions, we get

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

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

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

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

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

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

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

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 (10) and then from equation (C.12)

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

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

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

which replaces (15).

Equation (A.23) 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.24). Using $\dot{K}=0$ with public budget equilibium, it comes

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

which replaces (16). Therefore, from (C.15) and (C.17) with (C.16), let equation (A.33) 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

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

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

then

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

Finally

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

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