Optimal multi-level governance taking account of climate change and air pollution

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Abstract

We consider firms that combine variable inputs and capital goods that embody different technologies. Input use may cause simultaneously flow and stock externalities (e.g., air pollution and climate change). Regulatory bodies often address these externalities separately, failing to account for their interdependence, which leads to inefficient resource allocation. Based on a two-phase optimization approach, formulated in the context of CO_2 emissions, this paper determines the socially optimal coordinated taxation scheme. It also demonstrates that the presence of one externality magnifies the efficiency losses of the other. Therefore, non-coordinated taxation of the two externalities leads to over taxation. The analysis further determines the socially optimal taxation scheme of a second externality when the regulation/taxation of the first externality is already regulated and cannot be altered, a frequent challenge in multi-level governance. If the CO_2 emissions per unit of input depend on the employed technology, optimal policies require technology-differentiated tax schemes. Improving the precision of the CO_2 footprint of the variable inputs as a function of the employed technology not only helps to improve the implementation of a technology differentiated taxation scheme but most likely also the perception of social justice and consequently public acceptance of carbon taxes. A numerical example illustrates the methodological approach comparing coordinated and non-coordinated taxes.

Keywords: Multiple pollutants; multiple regulators, two-phase optimization; climate change; air-pollution, co-benefits

JEL classification: C61; H70; Q53; Q54

1. Introduction

There is a growing awareness that environmental policies that target certain objectives have unintended consequences that must be considered in policy design. Similarly, multiple government agencies pursue policy objectives, but coordination is challenging since externalities affect regulatory bodies at different jurisdictions and/or hierarchical levels. Ignoring these effects in the design of policies may affect the agents' behavior due to the changes in the margins and lead to suboptimal resource allocation (Bennear and Stavins 2007). Therefore, the design and implementation of a first-best policy must consider the complexity and interdependence of natural systems, interactions between policy tools, and their impact on agents' behavior (Peters 2018). Frequently, activities may cause several externalities. Some, like flow externalities, are immediate and have a predominantly local impact; others are cumulative stock externalities that often have a broader impact. However, there may be separate agencies that target flow effects and others that target stock effects, and frequently the corresponding policies are not coordinated, leading to inefficiency in resource allocation.

One obvious example of an activity that generates multiple externalities are CO_2 emissions associated with the burning of fossil fuels. It may cause a flow externality by degrading local air pollution. It may contribute to a stock externality, namely the accumulation of greenhouse gas emissions contributing to climate change. Local governments may regulate air pollution, but frequently not in coordination with the regulation of the stock externality. Another example is the application of toxic chemicals like pesticides. This may have acute, short-term effects by endangering humans and compromising environmental health. It also may cause the accumulation of contaminants in bodies of water that have long-term effects. Again, the regulation of the different impacts is done by different agencies without coordination and therefore, forgo significant welfare gains.

Three strands of literature aim to address this problem. The first is primarily empirical and analyzes the efficiency of mixed policy approaches. For example, studies (Aftab et al. 2010, Zhang and Xu 2018, Gren and Ang 2019) combine incentives with direct regulation to address multiple externality problems. The second strand is the double dividend literature which analyzes the welfare effects of the combination of policy instruments. This literature assumes a preexisting distortion and aims to improve the second-best solution to an externality problem given a budget constraint. This strand analyzes whether recycling of revenues of a tax on a negative externality is welfare-improving if used to reduce a preexisting distortionary tax (Goulder and Bovenberg 1996, Crago and Khanna 2014). Both strands of the literature assume that regulatory institutions are fully coordinated. The third strand of the literature analyzes the uncoordinated regulation of two externalities (Ambec and Coria 2018, Coria et al. 2021). In this case, regulations imposed to address one externality produce spillovers that affect the efficiency of regulating another. Some studies (Tahvonen 1991, Roseta-Palma 2002, Esteban and Dinar 2013) assume that a single agency considers multiple policy tools for addressing both flow and stock externalities. In contrast, the papers by Ambec and Coria (2018) and Coria et al. (2021) consider that agencies regulate the different externalities with different objectives. However, this analysis is static, and thus, it only does not allow to analyze of the dynamic dimension of the externality problem.[1]

This shortcoming of the previous literature is significant because dynamic elements are important for two reasons: the stock influences both: the stock and the flow externality – both externalities are interdependent. Dynamic elements, for example, scarcity costs of stock externalities are essential for most common property resources, such as forests (Food and Agricultural Organization of the United Nations 2016), fisheries (Clark 2006), or the quality and quantity of inland water bodies (European Environment Agency 2012). The correct management of these resources also requires considering flow externalities. In the case of fish or forests, substantial congestion costs frequently occur since the best harvesting sites are likely to be crowded. In the case of groundwater, a flow externality arises when water drawn by an individual farmer reduces the water tables (and increases pumping costs) of nearby wells (cone depression) more than that of distant wells. The linkage between CO_2 emissions and air pollution is an obvious example of a stock-flow relationship. However, flow and stock externalities occur together and are also interrelated.[2] At the same time, a certain extraction rate of a common property resource may lead to congestion if the stock is low; this may not occur if the stock is sufficiently high. Thus, the flow and stock externalities' magnitudes are interdependent, and their optimal levels need to be determined simultaneously. Determining the optimal externalities levels is challenging as it demands to define a specific policy instrument for each externality. However, the mathematical formulation of the social planner's decision problem with both externalities provides only a combined shadow value. That prevents designing instruments where each target a specific

[1] The authors assume in their study that each externality is caused by a different pollutant that interact. The emission of one pollutant is not essential for the emergence of the externality caused by the other pollutant. In contrast, in our study the same pollutant causes two different externalities. It seems to us a more accurate description for the studied case of air pollution and climate change.

[2] Literature reviews by Ebi and McGregor (2008), Nolte et al. (2018), (Anenberg et al. 2020) report robust evidence that climate change affects chemical and physical interactions that create, remove, and transport air pollution (ground ozone, particulate matter, pollen) leading to higher air pollution as climate change progress, commonly known by the term climate penalty. For example, an increase in the CO_2 concentration in the atmosphere leads to higher temperatures that in turn favor the formation of ground ozone. Longer, more intensive, and frequent heat waves favor wildfires that leads to an increase in particulate small matter ($PM_{2.5}$) and also to stationary or slowly migrating high-pressure systems that reduce dispersion, diffusion, and deposition of air pollutants.

externality. The optimal policy design is further complicated if different regulatory bodies do not pursue the same objectives. The existing literature paid very little attention to these problems. Only a few studies, like the articles by Haveman (1973), Brown (1974) and Mason and Polasky (1997), considered both types of externalities and determined the qualitative characteristics of the steady-state/optimal trajectories. However, none of these studies analyze the influence of multi-layer governments where each layer has its own objectives and agenda.

For analytic tractability, we assume that production units can choose the level of a continuous variable for each of their specific technologies. This assumption fits the case where farmers can choose water levels for each irrigation technology (gravity, sprinkler or drip). It applies to other instances where precision technologies (fluidized bed processors for drying or coating, high-efficiency air classifiers for cement manufacture, targeted paint spraying techniques for metals/wood and fuel-efficient appliances and automobiles) allow agents to use inputs more efficiently (Khanna and Zilberman 1997). The proposed modeling approach extends most of the previous literature that considers only single-layer governments (Goetz and Zilberman 2000, Sanchirico and Wilen 2005) and combines it with the literature on the technology choice (Zilberman et al. 2012) and multiple pollutants. Considering multiple technologies and locations enables the designing of differentiated technology policies targeting different externalities across space. This differentiation improves policy efficiency because of the more precise targeting. Moreover, better targeting improves the perception of social justice and, consequently, the public acceptance of regulations.

The structure of the model is presented in Section 2 of the paper. Section 3 introduces the two-phase optimization approach and determines the optimal public and private outcomes. The applicability of the two-phase approach to design policies for controlling air pollution and climate change are considered in Section 4, and several applications, demonstrating the versatility of the methodology, are presented in Appendix A. Section 5 provides a numerical example that illustrates the empirical relevance of the two-phase approach within the context of air pollution and climate change. The last section concludes the paper.

2. Model structure

To make the approach more intuitive, we present it as joint management of local air pollution (flow externality) and the atmospheric concentration of CO_2 (stock externality). The first phase determines the optimal input use and types of technologies for all agents for a given level of CO_2 emissions, denoted by Z, into the atmosphere and a given level of the externality stock, s. The choice of Z also determines the level of the flow externality given the pre-specified stock level. The value function of the first-phase optimization problem $V(Z;s)$ is then used as the objective function in the second-phase optimization problem (Section 3.3). Moreover, Z from the first phase becomes the choice variable in the second phase so that the solution to the second-phase problem allows determining the optimal level of aggregate CO_2 emissions at every moment of time.[3] The optimal trajectory of aggregate CO_2 emissions determines the trajectory of the stock, s. The two-phase approach[4] considers the interplay between the shadow price of the stock and the shadow price of the flow externality. It determines the magnitude of the deviation of each shadow price from the first-best solution.

To guide intuition for the methodological approach, one can think of the two-phase approach as an extension of the envelope theorem. The envelope theorem determines how the value of the objective function varies with changes in its parameters. The two-phase approach determines how the value function of the first phase (static optimization problem) varies with changes in a parameter. Instead of varying a parameter the two-phase approach nests a static within a dynamic optimization problem. The trajectory of the dynamic optimization problem is the analog of the varying parameter of the envelope theorem. By nesting the static within a dynamic optimization problem, the varying parameter of the first phase is chosen optimally over time. As a result, the shadow values of the static and dynamic problem are identical along the socially optimal trajectory.

2.1 Elements of the model

The model is based on N agents and that live on area of size H, e.g., H may indicate the number of square kilometer of a country. To reduce the complexity of the model we do not refer to a two-dimensional plane, but to a one-dimensional number line where every point of the line indicates a particular population density with respect to the fixed size of a location, e.g., density (number of agents) per square kilometer. The population density ε of every location falls within the range of 0 and $\boldsymbol{E}$, where $\boldsymbol{E}$ denotes the highest population density. The function $h(\varepsilon)$ denotes the probability density function of the population density over space, so that $\int_0^{\mathrm{E}} h(\varepsilon)\, d\varepsilon = 1$. Thus, $Hh(\varepsilon)$ denotes the size of the area that has the population density ε and $\varepsilon Hh(\varepsilon)$ the number of agents that live at locations with density ε. The consideration of "locations" is particularly important for the analysis of

[3] In a separate paper, the authors prove the equivalence of the solution of the single phase and two-phase problems for a wide variety of conditions – including those considered in this study.

[4] The two phases approach has been proposed originally by Goetz and Zilberman (2000), Xabadia et al. (2006), Goetz and Zilberman (2007). These authors analyzed the case of a single stock externality whereas in this study we consider a flow and a stock externality that are interdependent.

policy coordination because population densities are often related with jurisdictions and hierarchical levels of regulatory bodies. The variable t denotes calendar time with $t \in [t_0 , \infty]$, $s(t)$ is the stock of the CO_2 in the atmosphere, and its initial amount is $s(0) = s_0$. Each agent owns a single production unit that can be operated with technology $x(t,\varepsilon)$.[5] The domain of the variable x is given by $[0,1]$, where $x = 0$ denotes the traditional technology and $x = 1$ the most modern technology. Increases in the value of x represent more modern technologies. Production requires a generic variable input $u(t,\varepsilon) \in [0,\bar{u}]$ per production unit with technology $x(t,\varepsilon)$. For the purpose of our model one can think of energy as the generic input. The output per production unit at location ε is given by the function $f(u(t,\varepsilon))$ that is assumed to be strictly concave. Modern technologies are considered to be less polluting but do not affect production.[6] For example, modern technologies like three-way catalytic converters installed in cars or carbon storage technologies incorporated in industrial processes result in less carbon emissions. The per unit costs of the input employed by the production unit with technology $x(t,\varepsilon)$ are given by w. We assume that the demand for output is inelastic, and its price has been normalized to one. The rental or annualized fixed costs of the technology (e.g., to employ the services of contractors or purchase of equipment that can be resold), and the cost of technology licensing or other fees associated with improved input quality are denoted by $w^{fix}(x(t,\varepsilon))$ with $(w^{fix})' > 0$.

The function $\beta_0 - \beta_1(x(t,\varepsilon))$ relates the use of the input $u(t,\varepsilon)$ at locations with density ε with the emission of air pollutants. For the case of the traditional technology, emissions are equal to $\beta_0 u(t,\varepsilon)$, since $\beta_1(x(t,\varepsilon))$ is nonnegative and calibrated such that $\beta_1(0) = 0$ and $\beta_0 > \beta_1(1) > 0$. The term $\beta_1(x(t,\varepsilon)) > 0$ indicates to what extent modern technologies allow to reduce the emissions of air

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[5] Agents may produce goods or services for the market or for themselves. In the latter case they are considered traditionally as consumers, for example if agents use private or public transport, cook meals or heat their home. However, in order to reduce the notational complexity of the model we do not distinguish between market or household production and consider all agents as producers.

[6] By not taking account of a possible effect of modern technology on productivity allows us to concentrate without loss of generality on the presentation of the two-phase approach and the interplay between the two externalities The model could be naturally extended by considering $f((1+\alpha(x)x)u(t,\varepsilon))$, where $\alpha(x) \gtreqless 0$ indicates to what extent the modern technology is more or less productive than the traditional technology.

pollutants with respect to the traditional technology. The emissions with technology $x(t,\varepsilon)$ of all agents at a location with density ε are denoted by $U(t,\varepsilon)=\left(\beta_0-\beta_1\left(x(t,\varepsilon)\right)\right)u(t,\varepsilon)\varepsilon$. The damages of air pollution lead to additional costs that reduce the agents' net benefits. Air pollution is a flow externality as it has an immediate non-accumulating impact. Yet, it depends on the level of the stock externality - the accumulation of CO_2 in the atmosphere (Ebi and McGregor 2008, Anenberg et al. 2020). The damages or costs of the local air pollution are expressed by the function $c^L\left(s(t),U(t,\varepsilon)\right)$. We assume that c^L is strictly convex in s,x and u so that $c_s^L>0$, $c_u^L>0, c_{uu}^L>0$ and $c_x^L<0, c_{xx}^L<0$.[7] The damages or costs of climate change are expressed by the function $c^G(s)$ that is strictly convex in s.

The relationship between input use and the change in the stock variable is described by the function $\left(\kappa_0-\kappa_1\left(x(t,\varepsilon)\right)\right)u(t,\varepsilon)$, where the traditional technology leads to the highest emissions of CO_2 given by $\kappa_0 u(t,\varepsilon)$, since $\kappa_1\left(x(t,\varepsilon)\right)$ is nonnegative and calibrated such that $\kappa_1(0)=0$ and $\kappa_0>\kappa_1(1)$. Similarily to the case of air pollutants the function $\kappa_1\left(x(t,\varepsilon)\right)>0$ indicates to what extent modern technologies allow to reduce the emissions of CO_2 with respect to the traditional technology.

The agent's net benefits of production π with technology x at locations with density ε are given by $\pi=f\left(u(t,\varepsilon)\right)-wu(t,\varepsilon)-w_x^{fix}\left(x(t,\varepsilon)\right)$. To facilitate the reading of the paper we have summarized the notation of the functions and their arguments in Table 1.

[7] The subscript of a function specifies which variable to differentiate with respect to.

Table 1: Summary of the variables and their arguments

$t \in [t_0\ ,\ \infty\ ]$	Calendar time
ε	Location with a population density ε
$x(t,\varepsilon) \in [0,1]$	Emission abatement technologies employed at location with density ε at time t
$u(t,\varepsilon) \in [0,\bar{u}]$	Variable input per production unit operated with technology x at location with density ε at time t
$\left(\beta_0 - \beta_1\left(x(t,\varepsilon)\right)\right)u(t,\varepsilon)$	Emission of air pollutants at location with density ε at time t
$U(t,\varepsilon)$	Aggregate emission of air pollutants by all agents at location with density ε at time t
$s(t)$, $s(0) = s_0$	CO_2 concentration in the atmosphere a time t
$f\left(u(t,\varepsilon)\right)$	Output per production unit at location with density ε at time t
$c^L\left(s(t), U(t,\varepsilon)\right)$	Total costs or damages of the local air pollution at location with density ε at time t
$c^G(s)$	Total costs or damages of the CO_2 concentration in the atmosphere
$\left(\kappa_0 - \kappa_1\left(x(t,\varepsilon)\right)\right)u(t,\varepsilon)$	Emission of CO_2 at location with density ε at time t

For the remainder of the paper, we suppress the arguments t and ε of the employed functions whenever no ambiguity arises to reduce the notational burden.

2.2 The decision problem

We assume that a social planer aims to maximize the overall benefits of a region. Furthermore, we assume that the decision of the social planner does not affect the price of output. This is the case if market supply and market demand are formed on a far greater scale than the region the planner controls. The social planner's decision problem is

$$\max_{\substack{u(t,\epsilon),\\ x(t,\epsilon)}} \int_0^\infty \exp^{-rt}\left[\int_0^E \left[\left(f(u) - wu - w^{fix}(x)\right)\varepsilon - c^L\left(s(t),U\right)\right] Hh(\varepsilon)\, d\epsilon - c^G(s)\right]dt, \tag{1}$$

subject to

$$\begin{aligned} &\dot{s}(t) = \int_0^E \left(\left(\kappa_0 - \kappa_1(x)\right)u\varepsilon\right) Hh(\varepsilon)\, d\varepsilon - \varsigma s, \\ &s(0) = s_0,\ \ u \in [0,\bar{u}],\ \ x \in [0,1], \end{aligned} \tag{2}$$

where r denotes the social discount rate, and ς the natural decay rate of the CO_2 concentration in the atmosphere.

3. The private, local, national and the social optimums

We start our analysis by determining the optimal private outcome since it presents the case where none of the regulators at any hierarchy level intervened. For the analysis of the regulator's policy options at the different hierarchy level we solve for the socially optimal outcome from the perspective of a local planner and of the national planner. The first one takes account of local air pollution but not of climate change and the latter one of climate change but not of local air pollution. Thereafter, we solve for socially optimal outcome from the perspective of a social planner who considers jointly air pollution and climate change. The solution process of the socially optimal solution is broken down in two phases as it allows comparing the first phase with the solution of the local planner and the second phase with the solution of the national planner. In the first phase we analyze the socially optimal static component (flow externality). In the second stage we determine the socially optimal evolution of the static component over time which yields the dynamic component (stock externality). The obtained characteristics of the social optimum serve as a benchmark test for the evaluation of policy options to implement the socially optimal outcome, which is analyzed in Section 4.

3.1 The private optimum without intervention

Agents do not consider the flow or the stock externality and maximize only their private net benefits. The agent's decision problem is given by

$$\max_{u(\epsilon),x(\epsilon)} \pi = f\left(u\right) - wu - w^{fix}\left(x\right) \tag{3}$$

The solution of equation (3) yields the privately optimal input and technology choice for every production unit with technology x at location ε .[8] We denote this solution by $x^{PRIV}\left(\varepsilon\right)$ and $u^{PRIV}\left(\varepsilon\right)$.

3.2 The local regulator's optimum

We start our analysis by determining the local regulator's optimum for a given level of the stock s . The local regulator considers only the costs of air pollution as a result of their[9] local focus and the

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[8] Equation (3) is a simplified version of the private decision problem because in principle we had to include the terms c^L and c^G . However, to reduce the notational burden we do not present these terms in equation (3) since individual decisions on u and x have extremely small effects on the total costs of air pollution or climate change. Thus, we consider that their influence on the solution of equation (3) is negligible.

[9] Instead of the male and female pronoun, we use the plural form to facilitate reading.

negligible influence of the local CO_2 emission on the global evolution of the stock. Mathematically, the local regulator's problem at location ε reads as:

$$\max_{u(\epsilon),x(\epsilon)} \left(f\left(u\right) - wu - w^{fix}\left(x\right)\right)\varepsilon - c^{L}\left(s,U\right) \tag{4}$$

The first order conditions for the solution of problem (4) are:

$$\begin{aligned} &\left(f'\left(u\right) - w\right)\varepsilon - \frac{\partial c^{L}}{\partial U}\frac{\partial U}{\partial u} + \mu_1 - \mu_2 = 0, \forall \varepsilon \\ &\left(-\left(w^{fix}\right)'\left(x\right)\right)\varepsilon - \frac{\partial c^{L}}{\partial U}\frac{\partial U}{\partial x} + \mu_3 - \mu_4 = 0, \forall \varepsilon \end{aligned} \tag{5}$$

where μ_1, μ_3 and μ_2, μ_4 denote the Lagrange multipliers related with the lower and upper bounds of the decision variables u and x respectively. Equation (5) states that for every technology x and location ε the marginal private net benefits have to be identical to the sum of the marginal costs of air pollution with respect to u and the value of the Lagrange multiplier with respect to the boundary value of u. Similarly, equation (5) states that the marginal increase in the fixed cost as a result of choosing a less polluting technology x has to be equal to the sum of lower marginal costs of air pollution cost and the value of the Lagrange multiplier with respect to the boundary value of x .

Let us assume that the solution of the system of equations (5) provides a unique optimum that we denote by $u^{STAT}\left(\varepsilon;s\right)$ and $x^{STAT}\left(\varepsilon;s\right)$. To simplify notation, we refer to it by $\overline{STAT}\left(\varepsilon;s\right) = \left(u^{STAT}, x^{STAT}\right)$. When the flow but not the stock externality is considered, $\overline{STAT}\left(\varepsilon;s\right)$ yields the optimal input and technology choice for every production unit at the location with density ε for a given value of s .

To manage local air pollution without taking account of climate change, a regulator may impose taxes. They are specified in the following Definition.

Definition 1: *For an interior solution of equation* (5) *the tax on the input is given by* $\tau_u^{STAT} = \frac{1}{\varepsilon}\partial c^{L}/\partial u\Big|_{\overline{STAT}(\varepsilon;s)}$ *and on the production units by* $\tau_x^{STAT} = \frac{1}{\varepsilon}\partial c^{L}/\partial x\Big|_{\overline{STAT}(\varepsilon;s)}$*, where the subscript of the operator* " $|$" *specifies the evaluation points of the functions.*

The definition of the two taxes is derived from the first-order conditions of the equations (5). By inspection they show that $\left(f'\left(u\right) - w\right)\varepsilon - \tau_u^{STAT} = 0$ and $\left(w^{fix}\right)'\varepsilon - \tau_x^{STAT} = 0$ replicate the first-order conditions. Note that the taxes are differentiated with respect to the technology (e.g., certain types of technologies or certain vintages) and location ε (highly or less populated areas). The taxes τ_u^{STAT} and

τ_x^{STAT} are the shadow prices of an additional unit of the variable input with technology x and of the modernization of technology x at the location with density ε, respectively.

3.3 The social optimum when both externalities are considered

In the following two subsections we analyze the social optimum in two phases. In subsection 3.3.1 we focus on the flow externality and 3.3.2 on the stock externality.

3.3.1 First phase (flow externality)

To link the static with the dynamic problem we reformulate the static problem (4). Like before we determine the social optimum for a given level of the stock s but add the parameter Z that denotes the upper limit of aggregate CO_2 emissions, i.e., $\int_0^E \left(\left(\kappa_0 - \kappa_1 x\right)u\varepsilon\right)Hh\left(\varepsilon\right)d\varepsilon \le Z$. Hence, the static problem or the first phase of the social planner's decision problem is given by:

$$\begin{aligned} V(Z;s) = \max_{u(\varepsilon),x(\varepsilon)} & \int_0^E \left[\left(f\left(u\right) - wu - w^{fix}\left(x\right)\right)\varepsilon - c^L\left(s\left(t\right),U\right)\right]Hh\left(\varepsilon\right)d\epsilon \\ & + \lambda\left(Z - \int_0^E \left(\left(\kappa_0 - \kappa_1\left(x\right)\right)u\varepsilon\right)Hh\left(\varepsilon\right)d\varepsilon\right) \end{aligned} \tag{6}$$

where the Lagrange multiplier $\lambda \ge 0$ relates to the limitation of the aggregate CO_2 emissions over all technologies given the stock s. Given the concavity of the value function $V(Z;s)$, it holds that $V'(Z;s) > 0,\ V''(Z;s) < 0$.

The first order conditions of an interior solution for problem (6) are:

$$V_u \equiv \left(f'\left(u\right) - w\right)\varepsilon - \frac{\partial}{\partial u}\left(c^L\right) - \lambda\frac{\partial}{\partial u}\left(\int_0^E \left(\left(\kappa_0 - \kappa_1\left(x\right)\right)u\varepsilon\right)Hh\left(\varepsilon\right)d\varepsilon\right) = 0 \tag{7}$$

$$V_x \equiv -\left(w^{fix}\right)'\varepsilon - \frac{\partial}{\partial x_{jk}}\left(c^L\right) - \lambda\frac{\partial}{\partial x}\left(\int_0^E \left(\left(\kappa_0 - \kappa_1\left(x\right)\right)u\varepsilon\right)Hh\left(\varepsilon\right)d\varepsilon\right) = 0 \tag{8}$$

$$\int_0^E \left(\left(\kappa_0 - \kappa_1\left(x\right)\right)u\varepsilon\right)Hh\left(\varepsilon\right)d\varepsilon \le Z\,. \tag{9}$$

Equation (7) state that the marginal benefits of the input have to be equal to the sum of the marginal costs of air pollution and the shadow costs of the CO_2 emissions resulting from an increase in the input. Equation (8) states that the increase in the fixed costs of a more modern technology has to be equal to sum of the marginal costs of air pollution and the shadow costs of the reduction in CO_2 emissions resulting from a less polluting technology. Equation (9) put an upper limit on the CO_2 emissions. The solution of problem (6) for a given value of Z is denoted by $u^Z\left(\varepsilon;s\right)$, $x^Z\left(\varepsilon;s\right)$ and λ^Z. If we evaluate $Z > \int_0^E \left(\left(\kappa_0 - \kappa_1\left(x\right)\right)u\varepsilon\right)Hh\left(\varepsilon\right)d\varepsilon$ at u^{STAT} and x^{STAT}, and choose the value of Z such that any increase in Z does not lead to an increase in $V(Z;s)$ the shadow value of the aggregate CO_2 emissions is equal to zero, i.e., $\lambda^Z = 0$. If $Z = \int_0^E \left(\left(\kappa_0 - \kappa_1(x)\right)u\varepsilon\right)Hh(\varepsilon)\,d\varepsilon$ we denote the value of Z by Z^{STAT} and the shadow value by $\lambda = \lambda^{Z=Z^{STAT}} = 0$.[10]

3.3.2 Second phase (stock externality)

In the second phase, the value function of the first phase $V(Z;s)$ turns into the objective function of the dynamic decision problem and the parameter Z becomes the time-dependent decision variable $Z(t)$. Likewise, the stock variable becomes time-dependent, i.e., $s(t)$. With the solution of the dynamic decision problem, (10) - (11), we obtain the optimal value of aggregate CO_2 emissions $Z(t)$ over time:

$$\max_{Z(t)} \int_0^\infty \left(V(Z(t),s(t)) - c^G\left(s(t)\right)\right)e^{-rt}dt \tag{10}$$

subject to

$$\dot{s}(t) = Z - \varsigma s(t),\; s(0) = s_0. \tag{11}$$

The current-value Hamiltonian of the dynamic optimization problem (10) - (11) is given by

$$H = V(Z(t),s(t)) - c^G\left(s(t)\right) - \eta\left(Z - \varsigma s(t)\right), \tag{12}$$

where η denotes the co-state variable[11], i.e., the intertemporal user or scarcity costs of the concentration of CO_2 in the atmosphere. Then we also suppress the argument t of the control and stock variables unless necessary for an unambiguous notation. Let us assume that a unique solution of (10) - (11) exists and satisfies the first-order conditions:

$$H_Z = V_z(Z,s) - \eta = 0 \tag{13}$$

$$\dot{\eta} = \left(r + \varsigma + \frac{dc^G}{ds}\right)\eta - V_s(Z,s), \tag{14}$$

together with the corresponding transversality condition. The optimal trajectories of the choice and stock variables are denoted by $Z^{SOC}(t)$, $s^{SOC}(t)$ and $\eta^{SOC}(t)$. From the envelope theorem we know that $V_Z = \lambda$. Hence, along the optimal path, where $Z = Z^{SOC}$, we obtain from equation (13) that

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[10] When restriction (9) is not binding, the solution of problem (6) is given by u^{STAT}, x^{STAT}, and $\lambda^Z = 0$. The values of u^{STAT} and x^{STAT} only coincide with u^Z and x^Z_{jk} if $Z = Z^{STAT} = \int_0^E \left(\left(\kappa_0 - \kappa_1(x)\right)u\varepsilon\right)Hh(\varepsilon)\,d\varepsilon\Big|_{\overline{STAT}(\varepsilon;s)}$ and not otherwise.

[11] In equation (12) we have placed a negative sign in front of η so that it yields a strictly non-negative shadow price.

$$\lambda^{Z=Z^{SOC}}(t)=\eta \tag{15}$$

***Observation 1**: According to equation (15), the shadow value of the restriction of aggregate CO_2 emissions at the first phase, $\lambda^{Z=Z^{SOC}}(t)$, is equal to the shadow value $\eta(t)$ of the socially optimal concentration of CO_2 in the atmosphere in the second phase.*

Observation 1 expresses a key result of the study by showing that along the optimal path the shadow value of the flow externality is equal to the shadow value of the stock externality. This result is the consequence of nesting the static within the dynamic optimization problem. The evaluation of $V_u=V_x=0$ at x^Z,u^Z with $Z^{SOC}\le Z\le \int_0^E\left(\left(\kappa_0-\kappa_1(x)\right)u\varepsilon\right)Hh(\varepsilon)d\varepsilon\Big|_{\overline{STAT}(\varepsilon;s)}$ provides the shadow value λ^Z of local air pollution and CO_2 emissions contributing to climate change. If the value of Z is equal to Z^{SOC} an increase in the combination of the applied input and technology x at location ε is equal to the cost of the stock, η. Hence, evaluating $V_u=V_x=0$ where $Z=Z^{SOC}$ yields the values of x,u that are socially optimal when the costs of air pollution and climate change are considered. We denote these values by $x^{SOC}(\varepsilon;s),u^{SOC}(\varepsilon;s)$. or by $\overline{SOC}(\varepsilon;s)$ for a short-hand notation. If we evaluate $\int_0^E\left(\left(\kappa_0-\kappa_1(x)\right)u\varepsilon\right)Hh(\varepsilon)d\varepsilon$ at u^{SOC} and x^{SOC} , and choose the value of Z such that $\int_0^E\left(\left(\kappa_0-\kappa_1(x)\right)u\varepsilon\right)Hh(\varepsilon)d\varepsilon\Big|_{\overline{SOC}(\varepsilon;s)}=Z$, restriction (9) becomes binding. In this case λ is strictly positive and its value is denoted by λ^{SOC}. The value of λ^{SOC} can be derived either from equation (7) or (8) given the values of u^{SOC} and x^{SOC}. Based on equation (7) we obtain that

$$\lambda^{SOC}=\frac{\left(f'(u)-w\right)\varepsilon-\partial c^L/\partial u}{\partial Z/\partial u}\Bigg|_{\overline{SOC}(\varepsilon;s)}, \tag{16}$$

i.e., the shadow value of the concentration of CO_2 in the atmosphere is equal to the marginal social net benefits in terms of the marginal aggregate CO_2 emissions for the input. The right hand sign of equation (16) depends on u and x while the left-hand side does not. Thus, input and technologies have to be deployed over the locations ε such that the right-hand side is always equal to λ^{SOC}. The allocation of input and technologies over location ε is socially optimal when the constraint Z of the first phase is set equal to its socially optimal value, Z^{SOC}, and consequently the socially optimal employed input and the technology are given by $u^{SOC}=u^{Z=Z^{SOC}}$ and $x^{SOC}=x^{Z=Z^{SOC}}$. Thus, we can define the socially optimal taxes in the following observation.

***Definition 2**: The socially optimal taxes on the input at location with density ε, and on the technology x at location with density ε are given by $\tau_u^{SOC}(\varepsilon;s)=\frac{1}{\varepsilon}\partial c^L/\partial u\big|_{\overline{SOC(\varepsilon;s)}}$ and by $\tau_x^{SOC}(\varepsilon;s)=\frac{1}{\varepsilon}\partial c^L/\partial x\big|_{\overline{SOC(\varepsilon;s)}}$ respectively.*

The socially optimal taxes are specific for each ε given the level of the stock s. Since modern technology produce less air pollutant it holds that $c_x^L<0$, and therefore $\tau_x^{SOC}(\varepsilon;s)$ is actually a negative tax, i.e., it is subsidy. The shadow value of the aggregate CO_2 emissions can be related to the costs of air pollution $\lambda^{Z=Z^{STAT}}$, or to the costs of air pollution and climate change. The latter are obtained by the separation of the static and dynamic optimization problems. It corresponds to the sum of the costs of air pollution and the costs of the concentration of CO_2 in the atmosphere, i.e., $\lambda^{Z=Z^{STAT}}+\left(\lambda^{Z=Z^{SOC}}-\lambda^{Z=Z^{STAT}}\right)=\eta$. The evaluation of λ^Z at different values of Z opens new avenues for policy designs that take account of the interdependencies between local air pollution and the long-run effects of CO_2 emissions on climate change. The optimal design of policies is presented in the next section.

4. Policy options

In this section, we consider several policy scenarios. First, we determine the efficiency losses of the laissez faire situation compared to the socially optimal policy. We determine the part of the overall efficiency losses that can be attributed to air pollution and the part that corresponds to climate change. The results also show that adding a second externality on top of an already existing externality leads to higher efficiency losses of the second externality compared to the case where the second externality is the only existing externality. The reverse argumentation then implies that in the absence of the first externality the efficiency losses of the second externality decrease. Next, we consider the frequent case where the regulation of the different externalities is done by different regulatory bodies that need to be better coordinated. Thus, our analysis concentrates on the case where one regulator's policy needs to be adjusted to the pre-existing policy of another regulator to achieve ex-post efficiency. For example, local regulators have established local air pollution policies that a national regulator cannot modify. We show how climate policies need to be adjusted under these conditions to establish the socially optimal outcome. Moreover, we consider the opposite case and determine how local air pollution policies must be adjusted to consider preexisting climate change policies for establishing the socially optimal outcome. Finally, we look at the case where separate air pollution and climate change policies exist but are not coordinated and analyze its implications for negotiation between them. We determine the efficiency losses of uncoordinated policies where regulators do not take into account the interdependencies between the flow and stock externalities.

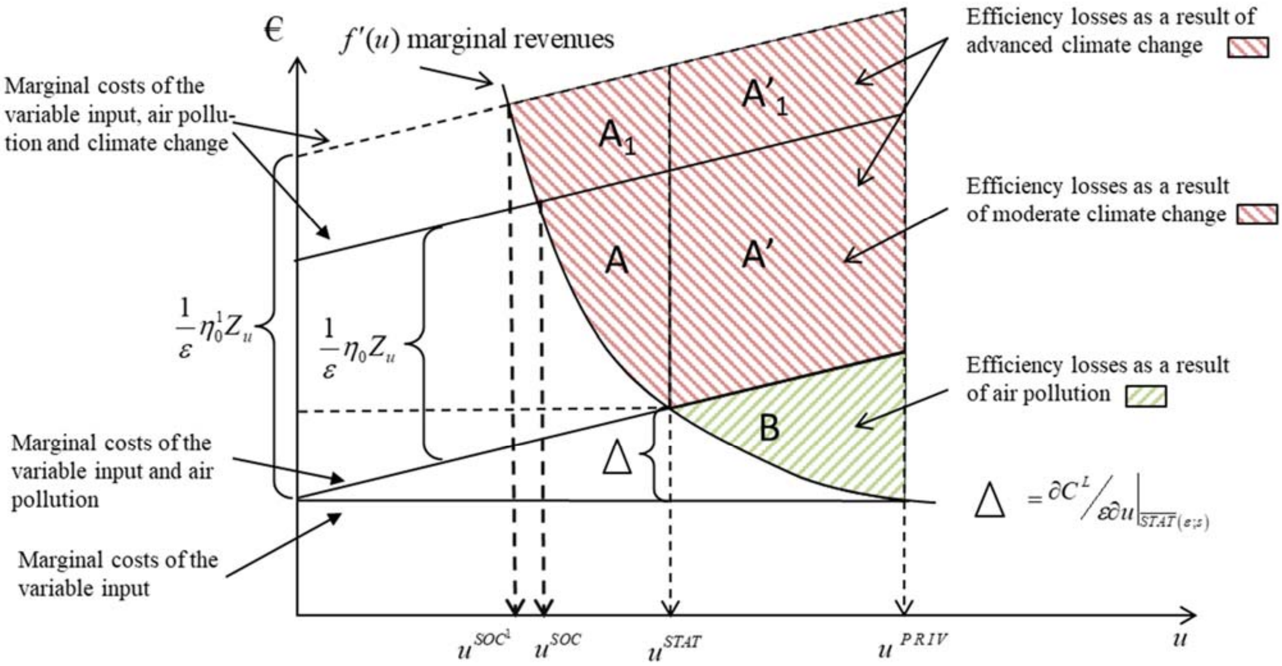
From Observation 1 we obtain that $\eta = \lambda$. Thus, we can write the first order conditions (7) and (8) as

$$\left(f'(u) - w\right)\varepsilon - \partial c^L/\partial u - \eta\left(\partial Z/\partial u\right) = 0, \quad -\left(w^{fix}\right)'\varepsilon - \partial c^L/\partial x - \eta\left(\partial Z/\partial x\right) = 0, \tag{17}$$

Equation (17) lends itself for a qualitative analysis. For this purpose we illustrate in Figure 1 the economic losses related to private solution $x^{PRIV}(\varepsilon;s), u^{PRIV}(\varepsilon;s)$ for a given density at location ε and a given stock s prior to any policy intervention. As above we use $\overline{PRIV}(\varepsilon;s)$ as a short-hand notation for these two values. To simply the graphical analysis of the economic losses we assume without loss of generality that the marginal costs of air pollution are linear in u, agents employ the technology x, and the values of ε and s are fixed. Figure 1 presents the economic analysis of the interplay between the changes in the costs of local air pollution and climate change as a result of an increase in the input. It illustrates the inefficiency losses caused by not considering the costs of both externalities. Since the stock in the first phase and also Z_u are constant, the marginal costs of climate change as a result of an increase in u, ηZ_u, are constant.[12]

Figure 1: Efficiency losses related to climate change and air pollution

[12] One can also think of Figure 1 as a graphical presentation of the first order condition of a single agent. However, variations of the input by a single agent alone have virtually no influence on the aggregate emissions given the large number of agents. Thus, the marginal costs curve of air pollution should be independent from the amount of input employed by a single agent Yet, agents are homogenous and every agent chooses the same abatement technology at a given ε, i.e., for given ε, $\beta_1(x)$ it is identical for all agents. Thus, the agents' aggregate emissions of air pollutants can be presented by the ε-times emissions of air pollutants by an individual agent, i.e., $\left(\beta_0 - \beta_1(x)\right)u\varepsilon$. In this way we can present the marginal costs of air pollution as a function of the single agent's use of the input. To simplify the graphical analysis of the Figures 1 and 3 - 6, we also consider that the cost curve of air pollution is a quadratic function of the agents' aggregate input. It allows to present the agent's marginal cost curve of air pollution as a linear function in u.



Let us assume that CO_2 emissions are not managed, and shortsighted agents ignore their contributions to local air pollution and climate change. Thus, every agent takes the other agents' actions as given and their optimal private choices strategies are determined by the solution of the first-order conditions of problem (3). Consequently, the optimum condition for an interior solution is given by the equivalence of marginal revenues $f'(u)$ and marginal costs w of the input attained by u_{jk}^{PRIV} . When the marginal costs of moderate climate change with respect to u , denoted by $\eta_0 Z_u$, and the marginal costs of air pollution with respect to u are not taken into account the aggregate difference between marginal revenues and costs leads to efficiency losses that are given by the areas *A*, *A*' and *B*. If all agents took the marginal costs of local air pollution into account or a regulator imposed the tax τ_u^{STAT} , their effort would be reduced by $u^{PRIV} - u^{STAT}$ and the efficiency losses would lessen as the areas *A*' and *B* were eliminated. The eliminated efficiency losses *A*' correspond to the reduced costs of moderate climate change, and the eliminated efficiency losses *B* correspond to the reduced cost in local air pollution.

Taking account of the effect of CO_2 emissions on air pollution and climate change lays the ground for the socially optimal use of the input u^{SOC} . If climate change has advanced (the CO_2 concentration in the atmosphere has increased) the associated marginal costs increase from $\eta_0 Z_u$ to $\eta_0^1 Z_u$, the socially optimal use of the input decreases from u^{SOC} to u^{SOC^1} and the associated efficiency losses increase by A_1 and A'_1 compared to the case of moderate climate change. Figure 1 shows the influence of the dynamics of the CO_2 concentration on the efficiency losses.

Moreover, Figure 1 permits to analyze to which extent technological change affects the efficiency losses of the two externalities. For example, when agents adopt a more polluting technology the slope of the marginal costs of air pollution will be more pronounced and therefore the efficiency losses of air pollution (exemplified by area B in Figure 1) will increase. The shadow price of climate change remains unchanged since the stock is constant in the first phase. Although it is optimal to use less of the input when a more polluting technology is adopted the efficiency losses related with climate change, given by the areas *A* and *A*', increase as well. Moreover, Figure 1 illustrates the interplay between the efficiency losses of local air pollution and climate change. Its interpretation yields the following proposition.

***Proposition 1**: If $f''(u)<0$, policies are absent and both externalities are negative and interdependent,*[13] *then efficiency losses of local air pollution magnify the efficiency losses of climate change or vice versa. The magnification effect increases with a decrease in the absolute value and the curvature*[14] *of $df(u)/du$.*

Proof: See Appendix B.

Proposition 1 can also be illustrated graphically by comparing the efficiency losses related with moderate climate change when air pollution is present (Figure 1) and when air pollution is absent (Figure 2), i.e., when CO_2 emissions only cause climate change but no local air pollution. The solution of the social maximization problem where c^L is set to zero yield the socially optimal u and x. They are denoted by u^{DYN} and x^{DYN} respectively and we use $\overline{DYN}(\varepsilon;s)$ as a short-hand notation for these two values. The corresponding marginal costs of climate change with respect to u are denoted by γZ_u. It holds that $u^{SOC}<u^{DYN}$ since it is determined by the equation $\left.\left(\left(f'(u)-w\right)\varepsilon-\gamma Z_u\right)\right|_{\overline{DYN}(\varepsilon,s)}=0$, instead of $\left.\left(\left(f'(u)-w\right)\varepsilon-\frac{\partial}{\partial u}\left(c^L\right)-\eta Z_u\right)\right|_{\overline{SOC}(\varepsilon,s)}=0$. In Figure 1 the efficiency losses of moderate climate change are given by *A* and *A'*. These efficiency losses are also shown in Figure 2. For this

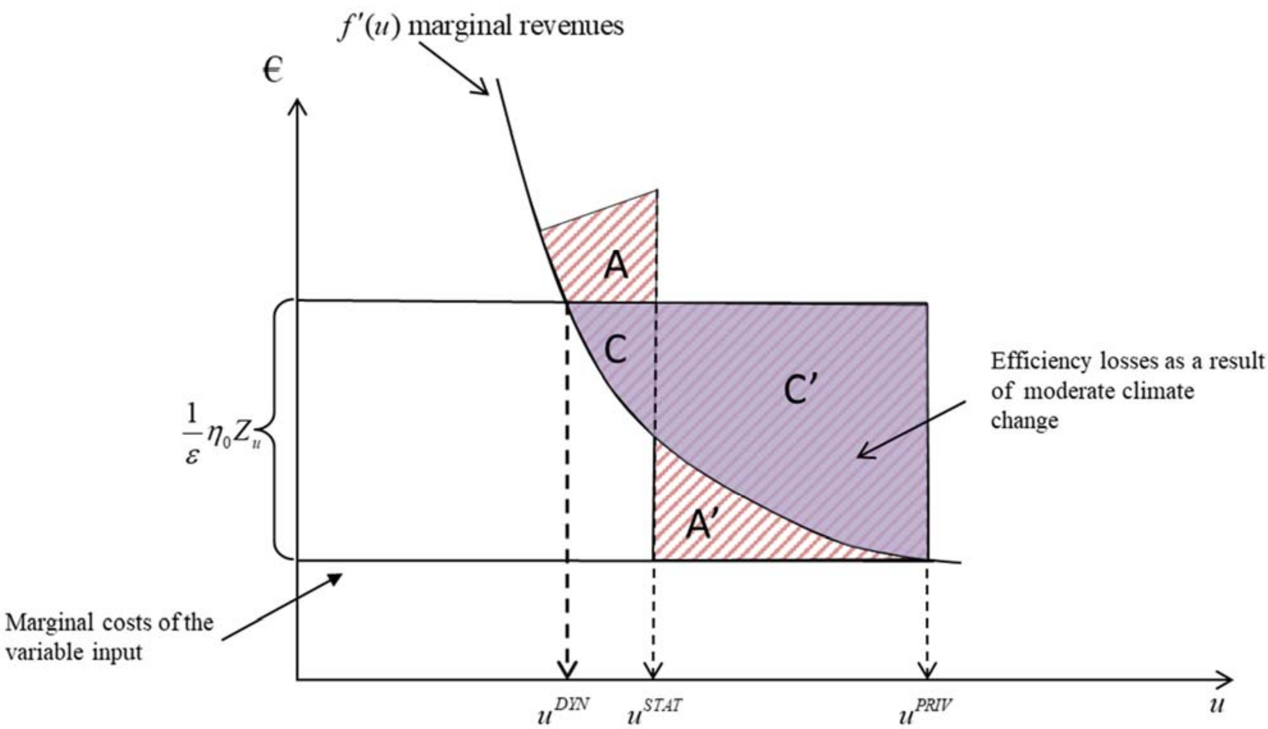
[13] The situation where both externalities are both positive or of opposite sign can be analyzed similarly and yield analogous results. For the sake of brevity these results are not presented here.

[14] The curvature measures how fast the unit tangent vector for instantaneous changes along the function $df(u)/du$ rotates (Pressley 2010). The stronger is the curve bent the larger are the instantaneous rate of changes of the direction of the unit vector.

purpose, maintaining the height and width of the parallelogram *A*' in Figure 1, it is transformed in Figure 2 into the rectangle $\left(u^{PRIV}-u^{STAT}\right)\frac{1}{\varepsilon}\eta_0 Z_u$. The area *A* is identical in the Figures 1 and 2. In Figure 2, however, the efficiency losses for climate change in the absence of local air pollution are given by the areas *C* and *C*'. Superimposing areas *C* and *C*' of Figure 2 on the diagonally stripped area *A* and *A*' of Figure 1 shows that efficiency losses of climate change are less in Figure 2. This reduction in efficiency losses is equivalent to the visible parts of *A* and *A*' in Figure 2. In other words, the existence of air pollution magnifies the efficiency losses of climate change.

By adding the costs of air pollution on the costs of climate change (reversed order of the emergence) one can also show that the costs of air pollution have increased in comparison to the costs of air pollution in Figure 1 (not shown in Figure 2). Thus, the pre-existence of a negative externality increases the efficiency losses of an additional negative externality and the order of the emergence of the externalities has not influence.

Figure 2: Efficiency losses related to climate change in the absence of air pollution



Reinterpreting Proposition 1 leads to the following observation.

Observation 2: *If $f''(u)<0$, policies are absent and both externalities are negative and interdependent, then a reduction in the efficiency losses of local air pollution strengthens the reduction in the efficiency losses of climate change or vice versa.*

If two externalities are present, reducing the efficiency losses of one externality magnifies the reduction of the efficiency losses of the other externality. This observation underlines the importance of technological progress. Using less polluting production units leads to a higher reduction of the costs of an externality if another externality is present compared to the case when it is not.

4.1. A tax on input and production units

The taxes specified in Definitions 1 and 2 are differentiated with respect to the input and the abatement technology. Its implementation requires that the regulator can monitor the input use and the employed technology since the agent's input tax varies with the chosen technology. Likewise, the optimal tax on the employed technology depends on the agent's input use. If the input is technology specific, for example cars powered by natural gas (CNG or NLG) input use and CO_2 emissions are closely related and the proposed taxes are directly implementable. However, if the input can be used across different technologies the accuracy of the relationship between input use and CO_2 emissions decreases because some technologies are more polluting than other given the same amount of input. For the latter situation our approach is less accurate. Thus, future research in advanced monitoring technologies, designing economic mechanisms that incentivize agents to reveal private information, or employing certified input applicators are necessary for improving the link between input use, technology, and CO_2 emissions. All three developments offer more data but also new kinds of data. In turn, they allow determining a more precise CO_2 footprint of input use that is likely to be a key element for the widespread implementation and public acceptance of technology-differentiated carbon taxes on input. The currently available monitoring technologies and economic mechanisms are frequently not advanced enough to generate a precise CO_2 footprint of input use and employed technologies. Therefore, regulators need to look for technically viable and economically acceptable second-best alternatives that allow for improving the precision of the CO_2 footprint, for instance by linking classes of inputs and types of technologies. For all example one can think of microchipping cars so that they can be identified at the gas station and taxes can be adjusted to the specific emissions level of the car.[15]

[15] With respect to air pollution an example could be to introduce a vehicle tax that increases with the CO_2 emissions/100km of the car and varies with the county/district/municipality to take air pollution into account. Thus, the difference between a vehicle tax in a big city and in some rural area should reflect the differences in the costs of air pollution.

Despite possible inaccuracies of our approach for an immediate application, the analysis of this section offers a blueprint in two directions. First, for the design of technology-differentiated policies with respect to input use, and second by demonstrating how uncoordinated policies related to interdependent externalities can be turned into first-best policies. We focus on the case of first-best policies to concentrate our analysis on the interdependence of the externalities and the non-alignment of the objectives of different regulators.

Assume that first-best policies as stipulated in Definition 2 are not available for a local regulator because she does not have the authority to define national climate policies. Alternatively, she may impose input and technology taxes $\tau_u^{STAT}(\varepsilon;s)$ and $\tau_x^{STAT}(\varepsilon;s)$, specified in Definition 1, to manage air pollution. Suppose the regulator at a later point in time (or a different regulator) wants to take account of the costs of climate change but cannot eliminate the already existing tax. In that case, the following question arises: What would the optimal tax that considers both the existing tax and the cost of climate change be? The optimal social outcome for an interior solution in the absence of any tax is established by x^{SOC}, u^{SOC} and $\eta Z_u\big|_{\overline{SOC}(\varepsilon;s)}$. The term $\eta Z_u\big|_{\overline{SOC}(\varepsilon;s)}$ denotes the shadow costs of an increase in the concentration of CO_2 in the atmosphere when the costs of local air pollution are already considered.

Proposition 2*: When local air pollution taxes are already in place the optimal climate change taxes on the input are*

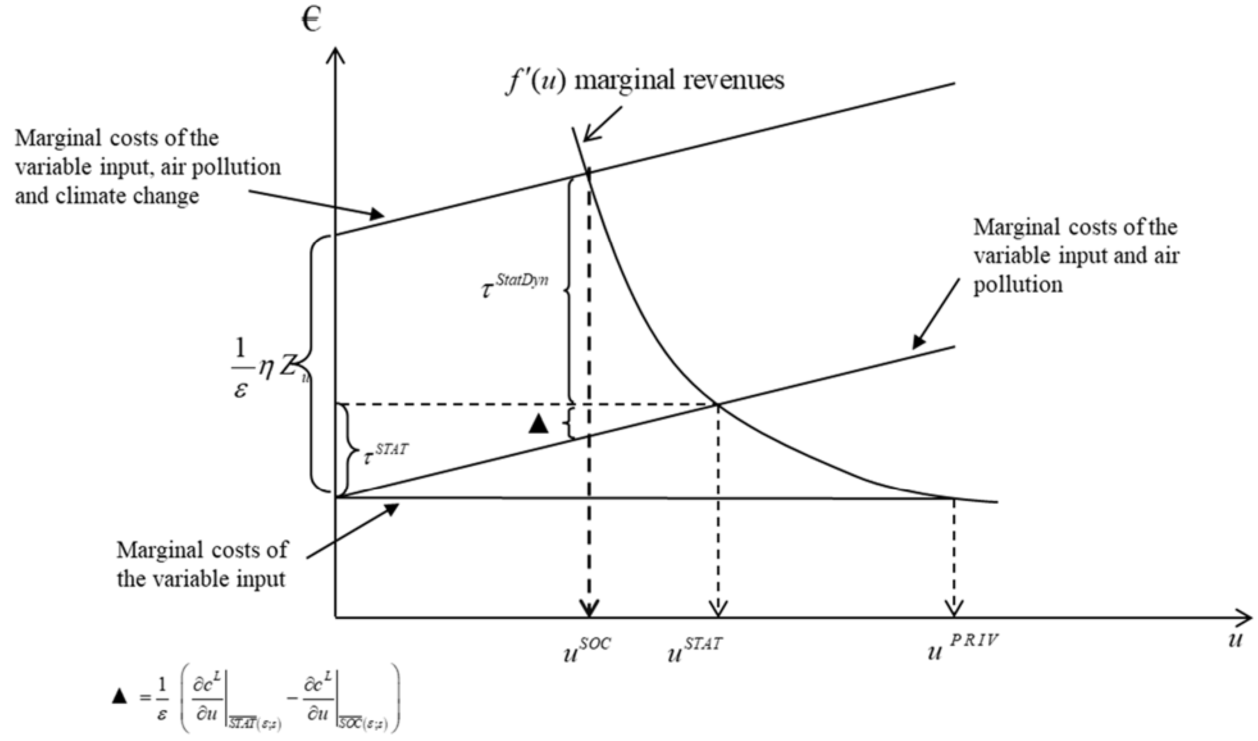
$\tau_u^{StatDyn}(t,\varepsilon) = \frac{1}{\varepsilon}\eta(t) Z_u\big|_{\overline{SOC}(\varepsilon;s)} - \frac{1}{\varepsilon}\left(\frac{\partial c^L}{\partial u}\bigg|_{\overline{STAT}(\varepsilon;s)} - \frac{\partial c^L}{\partial u}\bigg|_{\overline{SOC}(\varepsilon;s)}\right)$ *and on the employed technology*

$\tau_x^{StatDyn}(t,\varepsilon) = \frac{1}{\varepsilon}\eta(t) Z_u\big|_{\overline{SOC}(\varepsilon;s)} - \frac{1}{\varepsilon}\left(\frac{\partial c^L}{\partial x}\bigg|_{\overline{STAT}(\varepsilon;s)} - \frac{\partial c^L}{\partial x}\bigg|_{\overline{SOC}(\varepsilon;s)}\right)$. *The taxes are differentiated with respect to abatement technology x and location ε.*

Proof: See Appendix C.

The intuition for Proposition 2 is provided in Figure 3. The tax $\tau_u^{StatDyn}$ reflects the marginal costs of climate change $\frac{1}{\varepsilon}\eta Z_u\big|_{\overline{SOC}(\varepsilon;s)}$ minus the difference in the marginal costs of local air pollution $\frac{1}{\varepsilon}\left({\partial c^L}/{\partial u}\big|_{\overline{STAT}(\varepsilon;s)} - {\partial c^L}/{\partial u}\big|_{\overline{SOC}(\varepsilon;s)}\right)$ that are already considered in the tax τ_u^{STAT}. The difference in the marginal costs of local air pollution is indicated in Figure 3 by the symbol ▲ and indicates the absolute value of the amount that must be subtracted from $\frac{1}{\varepsilon}\eta Z_u\big|_{\overline{SOC}(\varepsilon;s)}$. This case is, for instance, relevant if a tax related to local air pollution is imposed within a smaller geographical or at a lower jurisdictional level while the tax on climate change is imposed within a larger geographical or at a higher jurisdictional level. As such, national regulators may have to accept the tax on local air pollution as given since its change is beyond their control. This case may occur if local air pollution was initially a pressing problem but not climate change. In fact, local air pollution in some metropolitan areas like Los Angeles or Mexico City was frequently regulated well before CO_2 emissions that contribute to climate change.

Figure 3: Socially optimal input tax $\tau_u^{StatDyn}$ if a preexisting tax on local air pollution τ_u^{STAT} has to be taken into account.



Likewise, there may exist taxes $\tau_u^{DYN}, \tau_x^{DYN}$ that take account of the costs of climate change but not of the costs of local air pollution. These preexisting taxes are derived from solving the social maximization problem, equation (2), where air pollution is not considered, i.e., c^L is set to zero. The pre-existing taxes in the absence of air pollution $\tau_u^{DYN}, \tau_x^{DYN}$ are given by the shadow price of the concentration of CO_2 in the atmosphere that is denoted in this case by γ. The optimal amount of input and production units with technology x are denoted by u^{DYN} and x^{DYN}, $\overline{DYN}(\varepsilon;s)$, respectively based on the concentration of CO_2 in the atmosphere s^{DYN}. Again, one may ask what the optimal additional tax $\tau_u^{DynStat}(t,\varepsilon)$ would be that considers the existing tax on the costs of climate change and the cost of local air pollution.

***Proposition 3**: When taxes to control for climate change are already in place, the optimal taxes to control air pollution are given by*

$$\tau_u^{DynStat}(t,\varepsilon)=\frac{1}{\varepsilon}\left(\left.\frac{\partial c^L}{\partial u}\right|_{\overline{SOC}(\varepsilon;s)}+\eta(t)Z_u|_{\overline{SOC}(\varepsilon;s)}-\gamma(t)Z_u|_{\overline{DYN}(\varepsilon;s)}\right) \text{ and}$$

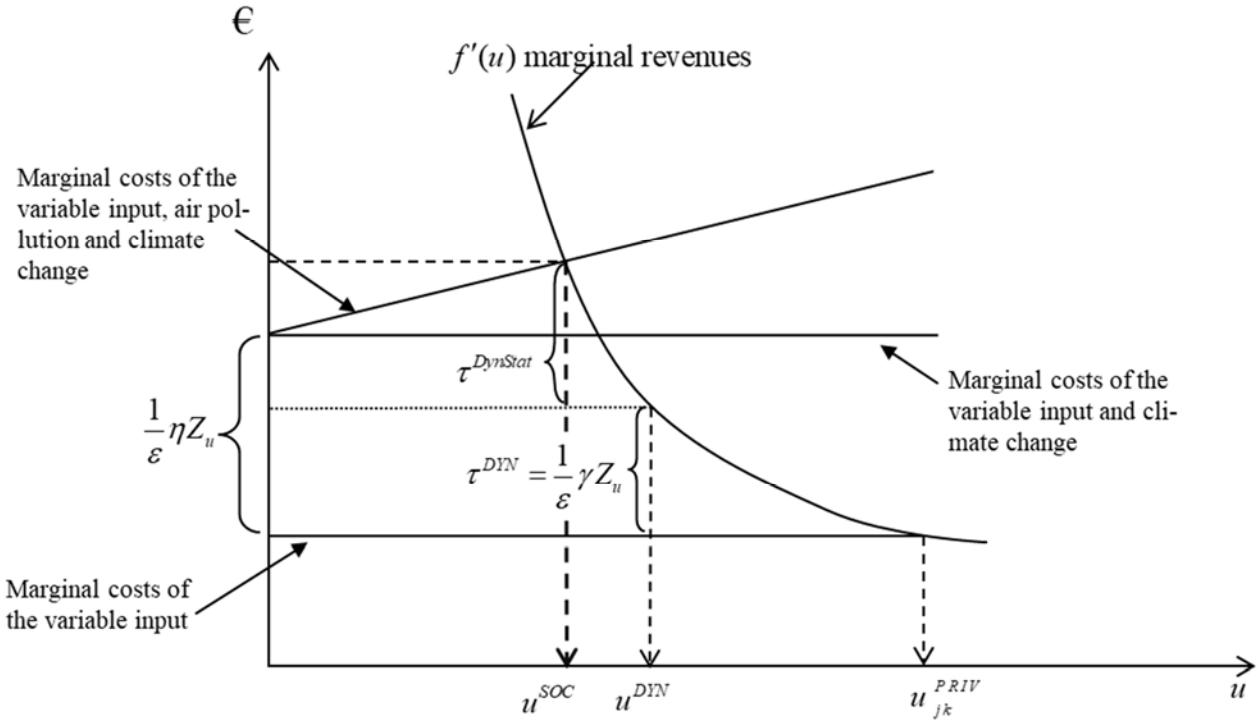
$$\tau_x^{DynStat}(t,\varepsilon)=\frac{1}{\varepsilon}\left(\left.\frac{\partial c^L}{\partial x}\right|_{\overline{SOC}(\varepsilon;s)}+\eta(t)Z_u|_{\overline{SOC}(\varepsilon;s)}-\gamma(t)Z_u|_{\overline{DYN}(\varepsilon;s)}\right)$$

on the variable input and the employed abatement technology respectively. The taxes are differentiated with respect to locations with density ε.

Proof: See Appendix D.

The intuition for Proposition 3 is provided in Figure 4. The tax $\tau^{DynStat}$ indicates that the tax on the variable input should include the marginal costs of local air pollution and be corrected by the difference between the shadow prices of the CO_2 concentration in the atmosphere $\frac{1}{\varepsilon}(\eta Z_u-\gamma Z_u)$. This case is relevant if local air pollution is considered a minor problem, but climate change as a more pressing problem. For instance, in different metropolitan areas in Europe, like in Barcelona or Madrid, air pollution was not regulated locally before 2015 while the EU and all its member states had ratified the Kyoto Protocol already in 2002. Similarly, in less densely populated or agricultural areas climate change might be considered a more important problem than air pollution and therefore no local legislation was passed although climate change regulation had come into effect before.

Figure 4: Socially optimal input tax $\tau_u^{DynStat}$ if a preexisting tax on climate change τ_u^{DYN} has to be taken into account.



In the case where neither of the two regulators considers the preexisting taxes and both act independently, we can compare the taxes of non-coordinated taxation with those of coordinated taxation (socially optimal taxation). For this purpose, we define the socially optimal taxes τ_u^{SOC} and τ_x^{SOC}. Based on equation (17) they are given by $\tau_u^{SOC}(t,\varepsilon) = \frac{1}{\varepsilon}\left(\partial c^L/\partial u\big|_{\overline{SOC}(\varepsilon;s)} + \eta(t) Z_u\right)$ and $\tau_x^{SOC}(t,\varepsilon) = \frac{1}{\varepsilon}\left(\partial c^L/\partial x\big|_{\overline{SOC}(\varepsilon;s)} + \eta(t) Z_u\right)$. Furthermore, we observe in Figure 4 that $\frac{1}{\varepsilon}\gamma Z_u$ is less than $\frac{1}{\varepsilon}\eta Z_u$. The intuition for this ordering is that agents emit more CO_2 if they face a tax that only takes account of the costs of climate change than if they face a tax that takes account of climate change where air pollution has been considered. Thus, τ_u^{DYN} produces higher CO_2 emissions than τ_u^{SOC}, and consequently the concentration of CO_2 and the corresponding shadow price of the concentration of CO_2 in the atmoshere γ will be higher for τ_u^{DYN} than the corresponding shadow price of the concentration of CO_2 in the atmoshere η for τ_u^{SOC}. We can now compare the taxes of non-coordinated taxation with the socially optimal taxes.

Proposition 4*: The sum of non-coordinated taxes on input to correct separately for air pollution and climate change are higher than the socially optimal tax on input that takes into account both externalities, i.e.,* $\tau_u^{STAT} + \tau_u^{DYN} > \tau_u^{SOC}$ *The sum of non-coordinated subsidies on the technology to correct separately for air pollution and climate change are smaller than the socially optimal subsidy on the technology that takes account of both externalities, i.e.,* $\tau_x^{STAT} + \tau_x^{DYN} < \tau_x^{SOC}$.

Proof: See Appendix E.

Proposition 4 shows that non-coordinated policies lead to an excessive taxation of the input compared to the socially optimal (coordinated) policy if the non-coordinated and the coordinated taxation regime led to an identical mix of technologies. For the case where the function c^L is linear in x the taxes τ_x^{STAT} and τ_x^{DYN} depend on u but not on x. The higher tax per unit of input of the non-coordinated policies leads to less input use compared to the socially optimal tax. Consequently, the taxes on technology x are smaller for the case on non-coordinated policies than for the coordinated policies (socially optimal taxes).

5. Numerical example

This section presents a numerical analysis to illustrate the theoretical model. At this stage, the parametrization is based on hypothetical data, but the framework is designed to accommodate real-world data in future applications. The analysis highlights the welfare implications of the proposed policies. To achieve this, we examine four different scenarios. The benchmark by which we evaluate the policies is the private solution, which will be taken as the baseline. In addition, we simulate the following cases:

(1) the optimal solution of the local government when climate change is not considered (local regulation)
(2) the optimal solution of the national government, which does not take local pollution into account (national regulation)
(3) the social optimum, when both externalities are considered simultaneously.

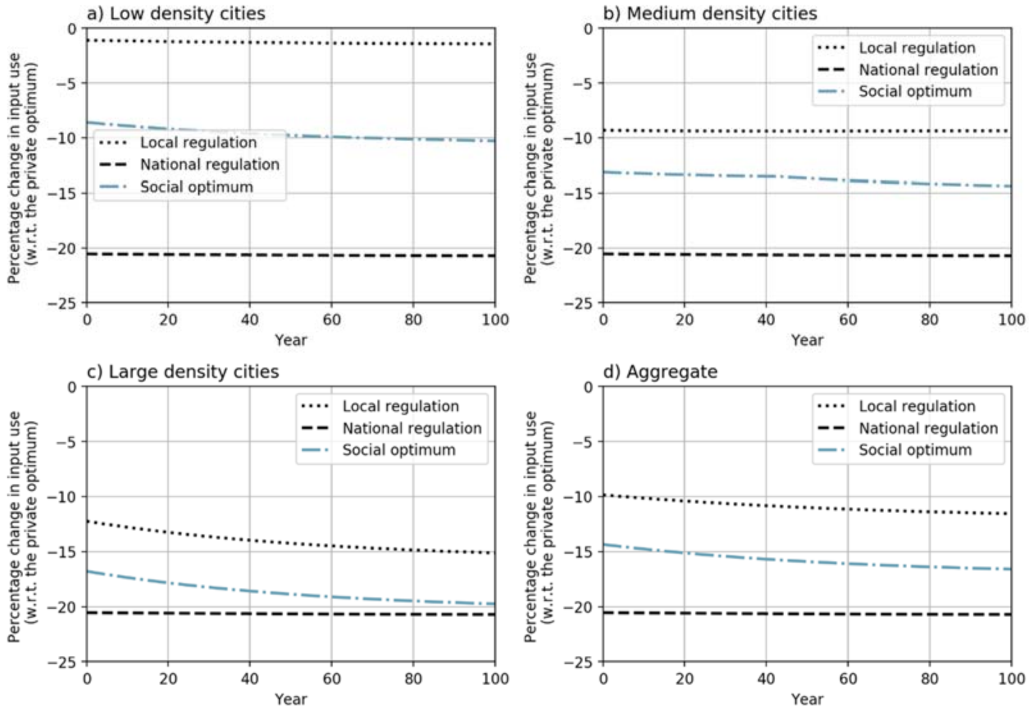
Table 2 provides a summary of the parameters and functions utilized in the numerical analysis. With these specifications, all derivatives conform to the assumptions of the theoretical model. The solutions for the different scenarios are computed over a timeframe of 100 years.

Table 2: Summary of functions and parameters in the model

ε	$[1,38]$
$f\left(u\left(t,\varepsilon\right)\right)$	$61060\ u^{0.37}$
w	10000
$w^{fix}\left(x\left(t,\varepsilon\right)\right)$	$1000\left(0.5+\frac{x}{2}\right)^{0.8}$
$\left(\beta_0-\beta_1\left(x\left(t,\varepsilon\right)\right)\right)u\left(t,\varepsilon\right)$	$\left(1-0.4\left(x\left(t,\varepsilon\right)\right)\right)u\left(t,\varepsilon\right)$
$c^L\left(s\left(t\right),U\left(t,\varepsilon\right)\right)$	$5\left(\left(1+0.001s\right)U(t,\varepsilon)\right)^2$
$c^G\left(s\right)$	$4s^2$
$\left(\kappa_0-\kappa_1\left(x\left(t,\varepsilon\right)\right)\right)u\left(t,\varepsilon\right)$	$\left(1-0.2\left(x\left(t,\varepsilon\right)\right)\right)u\left(t,\varepsilon\right)\varepsilon$
s_0	400
ς	0.015
r	3%

For each scenario, we illustrate the evolution of input use, technology levels, and the stock of CO_2 in the atmosphere. We begin by depicting the evolution of input use for each policy scenario as a percentage over the private optimum across low, medium, and high-density locations (Figure 5, panels a – c), and in aggregate (Figure 5, panel d). Notably, the regulation of air pollution results in varying degrees of input reduction depending on density levels. In low-density cities, the reduction of input use is nearly negligible. However, in medium-density cities, input use decreases by approximately 10%, while in large-density cities, it declines from approximately 12% at the beginning of the temporal horizon to 15% in the steady state. On the other hand, the national regulator, primarily focused on climate change as a global externality, should impose a location-independent reduction in input use. In this case, the optimal policy leads to a uniform reduction of approximately 21% compared to the private optimum. Finally, in the social optimum scenario, which accounts for both air pollution and climate change, input use reductions vary by location. In low-density cities, reductions range from 8% to 10%; in medium-density cities, from 13% to 14%; and in large-density cities, from 17% to 20%.

Figure 5: Percentage change in input use with respect to the private optimum



Additionally, Figure 6 (panels a – c) illustrates technology adoption over time across various locations. In both the local regulation and the social optimum scenarios, the level of technology adoption varies based on location density. In low-density cities, where pollution levels tend to be relatively lower, there exists less urgency to adopt new technologies. However, in medium-density cities, where pollution gradually accumulates in the atmosphere due to increased CO_2 emissions, there is an increase in the adoption of less polluting technologies over time. This response is driven by the need to mitigate local air pollution damages. The pattern of relatively quick adoption of newer and less polluting technologies shown in Figure 6b is a consequence of the high cost of accumulating pollution with a quadratic damage function. In large-density cities, where pollution levels are typically higher, new technologies must be adopted immediately to mitigate environmental damages.

In contrast, due to the limitations of the national regulator, which imposes a uniform tax irrespective of location, the technology level is identical across all locations. It starts at 0.49 at the beginning of the time horizon and stabilizes at approximately 0.51 at the end.

Figure 6: Evolution of technology level

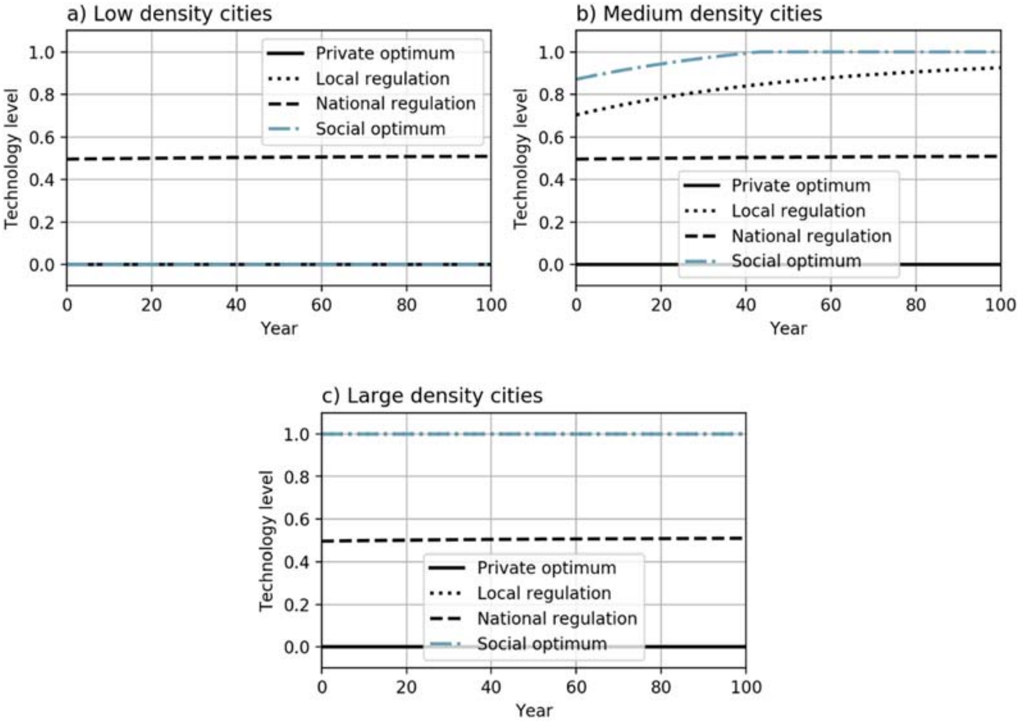
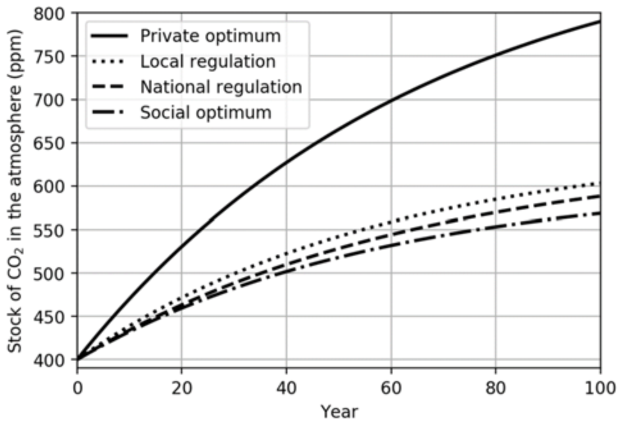


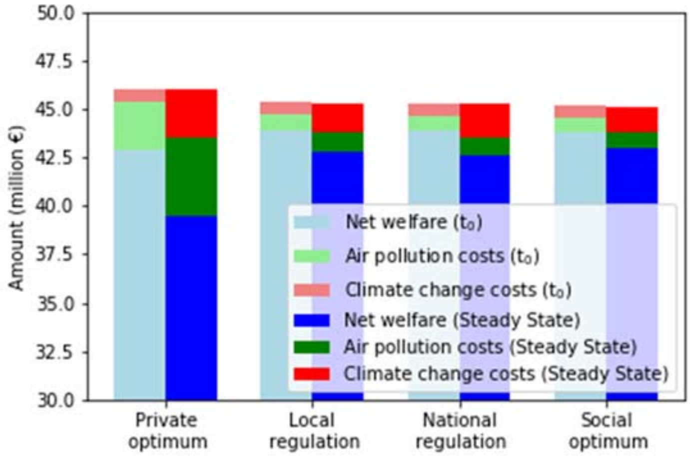
Figure 7 displays the evolution of the pollution stock over time. In the absence of any policy intervention, atmospheric CO_2 levels reach 790 ppm at the end of the time horizon. However, the figure shows that all three policy approaches effectively slow the growth of greenhouse gas emissions. Both the local regulation, which fails to internalize the marginal shadow price of pollution stock in agents' decisions, and the national regulation, which overlooks the air pollution externality, lead to a slightly higher steady-state pollution level compared to the social optimum scenario.

Figure 7. Stock of CO_2 in the atmosphere



Finally, figure 8 illustrates the welfare implications of the alternative policies compared to the baseline scenario. It depicts air pollution costs, climate change costs, and net welfare levels, both at the initial time period and at steady state. The sum of these three components represents the gross benefits. In the absence of policy intervention, the economic costs attributable to air pollution and climate change are projected to represent 10.3% and 6.3% of the private gross benefits, respectively, once the system reaches a steady state. However, policy implementation significantly alters this outcome, leading to a significant improvement in overall welfare.

Figure 8. Air pollution costs, climate change costs and net welfare of the policies



The numerical example has presented the optimal solution for the local government when climate change is not considered, the optimal solution for the national government when they overlook air pollution damages, and the social optimum, where both externalities are addressed simultaneously. Although for the given parameter values the overall net welfare of the local and national regulation and of the social optimum are only slightly different, the regulation at different regional scale may include subsidies and taxes that overregulate at one level and underregulate at a different level. The proposed framework can be used to determine the optimal input and technology policies of local or national governments while accounting for pre-existing regulations. The precise analysis of the numerical model is the current object of the ongoing work of this research.

6. Summary and conclusions

Traditionally, environmental and resource economics has focused on managing an externality caused by a particular pollutant or by the extraction of a particular natural resource. Yet, the complexity of natural systems and the interdependency of their different components makes it hardly possible to target a single externality without provoking unintended externalities and changes in the economic margins of the agents. As a result, their behavior is not only affected by policy measures but also as the consequence of the unintended side effects.

Conventionally, economists advise a specific policy instrument for each externality. However, the multiplicity of externalities is often reflected by a great variety of regulatory bodies at different jurisdictions and hierarchical levels with heterogeneous competences and missions. This policy context presents a challenge for policy coordination since interactions between externalities and interferences between different policy instruments complicate the design and implementation of a first-best policy that can consider the resulting behavior of the agents, the interrelationships within and between natural systems and the fact that some externalities are stock externalities, while others are flow externalities. Policies designed by different regulatory bodies may interfere with each other since they may have differing missions and preexisting policies may be inalterable. To improve the design of policies related to natural resources and ecosystem services, we present a two-phase approach for the coordination of policies.

The two-phase approach allows determining separate shadow values for interdependent flow and stock externalities. Even though a regulatory body had defined a policy for an externality that is not socially optimal the two-phase approach allows the second regulatory body to determine a policy for another externality such that the set of both policies is socially optimal. In other words, the two-phase approach allows establishing the first-best outcome even if the regulatory bodies do not cooperate, or the pre-existing policy cannot be abandoned. The paper also shows the importance of the implementation of a technology differentiated input tax if inputs can be used across different technologies. In this case advanced monitoring technologies, innovative mechanisms to incentivizes agents to reveal private information or a certified input use are necessary to establish a close link between input use and CO_2 emissions. A high precision of the CO_2 footprint of variable inputs is not only important for establishing the social optimum but also for achieving social justice which in turn favors public acceptance of carbon taxing.

Appendix

A. Generalization and applicability of the proposed methodology

The applicability of the two-phase optimization approach has been discussed above in the context of air pollution and climate change. A second example illustrates the case of common property resources. It may apply to cases where agents harvest for instance fish from a lake or the open sea, or the case of timber harvesting from a common property forest. In the case of fisheries or tree logging, the sites with the best cost-benefit ratio access are likely to be visited more frequently (Smith 1968, Sterner et al. 2018). For instance, for some sites the access costs may be lower than for other sites and similarly some sites may offer higher quality fish or trees than others. Once the number of agents exceeds a site- and stock-specific threshold agents impose costs on each other due to congestion/crowding (Heintzelman et al. 2009, Hughes and Kaffine 2017). Given that agents fail to account for the costs they impose on others, one concludes from the perspective of a social planner that sites with the best cost-benefit ratio are likely to be over-fished or over-harvested under open access (Hughes and Kaffine 2017). The existence of congestion costs is a flow externality that should be considered in the objective function of a social planner. In our previous example of air pollution and climate change the congestion costs are conceptually identical to local air pollution and the stock of fish or trees to the concentration of CO_2 in the atmosphere.

A third example is groundwater management by multiple agents. The extraction of groundwater allows air to enter in the porous zone of the soil. If more water is extracted than water is flowing in from adjacent locations, it results in the drawdown of the water table at the location of the well. Consequently, the water table surrounding the well slopes down and forms a cone with its center at the bore well. The higher is the difference between extraction and replenishment, the larger will be the cone of depression. Thus, if the distance between different wells is short and many wells are nearby a large amount of water drawn by one agent reduces the water tables of nearby wells (cone depression) more than that of distant wells. Thus, the aggregate extraction of an agent's neighbors produces temporarily additional costs for her (Brown 1974, Kovacs et al. 2015, Rad et al. 2021). In this case the cone depression is related to the flow externality and the evolution of the overall water table to the dynamic externality. A fourth example is related to the management of toxic material, like pesticides, herbicides, or the production of toxic chemical agents. The use of toxic material often leads to gradual release of a contaminant that accumulate at a final receptor (e.g., people, wildlife, surface water, soil). The accumulation of the contaminant gives rise to a stock externality. At the same time, the production, management, and application of the toxic material implies the risk of accidents that may damage human beings, wildlife, or distinct environmental compartments. In this way, the expected value of the hazard of an accident presents a flow externality related to the management and/or production of toxic material.

The previous four examples considered the case of agents that maximize their private net benefits where externalities were not considered. However, a social planner that maximizes the utility of society considers the costs that every agent inflicts on all other agents. For the social planner the flow externality becomes a coordination problem that must be solved at every moment of time together with the optimal intertemporal management problem of the stock variable. Frequently the coordination problem becomes a spatial decision problem. For example, this is the case where agricultural runoffs (nitrogen or phosphor) lead to the pollution of surface or groundwater (Goetz and Zilberman 2007, Xabadia et al. 2008). The choice variables depend in this example not only on time but also on an index that reflects the hazard level of the agent's agricultural land for water pollution, i.e., proximity to the water body, slope, soil texture etc. Thus, the pollutant-load not only depends on the amount of organic or mineral fertilizer applied but also on the location where it has been applied. The overall pollutant-discharge increases disproportionally, the more fertilizer has been applied at the more vulnerable areas for runoffs compared to less vulnerable areas. The last example relates to biodiversity and enrollment of agricultural land in conservation programs. During the first phase of the program the social planner needs to determine the optimal spatial enrollment of the land considering the size, quality and connectedness of the enrolled land subject to a required degree of biodiversity. In the second phase the degree of biodiversity turns into the decision variable and the net benefits function of the first phase becomes the objective function of the second phase augmented by a function that describes the dynamics of the degree of biodiversity.[16] All six examples show that the proposed two-phase approach has a high potential to be applied in environmental and resource economics and other areas of economics.

B. Proof of Proposition 1

Based on equation (17) we determine the efficiency losses when choosing u^{PRIV} and x^{PRIV} instead of u^{SOC} and x^{SOC} by the area $\int_{u^{SOC}}^{u^{PRIV}} \left(\left(w + \frac{\partial}{\partial u}\frac{1}{\varepsilon}\left(c^{L}\right) + \frac{1}{\varepsilon}\eta Z_{u} \right) - f'(u) \right) du > 0$. The integrand is zero when $u = u^{SOC}$ and $x = x^{SOC}$ as required by the first order condition for a maximum. For higher values of u

[16] Recently Banerjee et al. (2021) analyzed this type of spatial coordination problem within a static context in a laboratory environment. The authors focused on the bidding behavior of private farmers and not on the social planner's perspective.

and corresponding values of x the integrand is positive since $f''' < 0$, $\left.\frac{\partial^2}{\partial u \partial u}\left(c^L\right)\right|_{x^{SOC}} > 0$, and the terms w and η do not depend on u. If air pollution is absent, i.e., when CO_2 emissions cause climate change but no local air pollution, the socially optimal choice variables are given by u^{DYN} and x^{DYN}. In this case the efficiency losses of climate change are given by $\int_{u^{DYN}}^{u^{PRIV}} \left(+w + \frac{1}{\varepsilon} \eta Z_u - f'(u) \right) du > 0$. However, when air pollution is present the employed amount of the generic input is reduced by $u^{DYN} - u^{SOC}$ and thus, efficiency losses of climate change are given $\int_{u^{SOC}}^{u^{PRIV}} \left(+w + \frac{1}{\varepsilon} \eta Z_u - f'(u) \right) du$. A comparison of the last two integral shows that the efficiency losses of climate change increase in the presence of an additional externality and corresponds two $\int_{u^{SOC}}^{u^{DYN}} \left(+w + \frac{1}{\varepsilon} \eta Z_u - f'(u) \right) du$. Figure 1 illustrates that the additional efficiency losses increase with a decrease in the absolute value of the slope and also in the curvature of the marginal revenues function. Moreover, since neither of the two externalities is positive the marginal revenue curve does not shift upward. Therefore, efficiency losses of the privately optimal solution increase the lower is the socially optimal input use. □

C. Proof of Proposition 2

In the presence of pre-existing taxes on air pollution τ_u^{STAT} the agents' first-order conditions for the first-best outcome are given by $f'(u) - w - \tau_u^{STAT}(\varepsilon) - \tau_u^{StatDyn}(t,\varepsilon) = 0$ and $-\left(w^{fix}\right)' - \tau_x^{STAT}(\varepsilon)$ $-\tau_x^{StatDyn}(t,\varepsilon) = 0$ where $\tau_u^{StatDyn}$ and $\tau_x^{StatDyn}$ indicate taxes that introduce the costs of climate change but also take account of the existing tax/subsidy on local air pollution at location ε given the stock s. The first-order conditions of the first-best outcome are recovered if $\tau_u^{StatDyn}(t,\varepsilon)$ is chosen such that $\frac{1}{\varepsilon}\left.\left(\partial c^L / \partial u\right)\right|_{\overline{STAT}(\varepsilon;s)} + \tau_u^{StatDyn}(t,\varepsilon) = \frac{1}{\varepsilon}\left(\left.\left(\partial c^L / \partial u\right)\right|_{\overline{SOC}(\varepsilon;s)} + \eta(t) \left. Z_u \right|_{\overline{SOC}(\varepsilon;s)} \right)$ and $\tau_x^{StatDyn}(t,\varepsilon)$ such that $\frac{1}{\varepsilon}\left.\left(\partial c^L / \partial x\right)\right|_{\overline{STAT}(\varepsilon;s)} + \tau_x^{StatDyn}(t,\varepsilon) = \frac{1}{\varepsilon}\left(\left.\left(\partial c^L / \partial x\right)\right|_{\overline{SOC}(\varepsilon;s)} + \eta(t) \left. Z_u \right|_{\overline{SOC}(\varepsilon;s)} \right)$. Thus, the adjusted tax on the input is given by $\tau_u^{StatDyn}(t,\varepsilon) = \frac{1}{\varepsilon}\eta(t) \left. Z_u \right|_{\overline{SOC}(\varepsilon;s)} - \frac{1}{\varepsilon}\left(\left.\left(\partial c^L / \partial u\right)\right|_{\overline{STAT}(\varepsilon;s)} - \left.\left(\partial c^L / \partial u\right)\right|_{\overline{SOC}(\varepsilon;s)} \right)$ and on the production unit with technology x it is given by $\tau_x^{StatDyn}(t,\varepsilon)=\frac{1}{\varepsilon}\eta(t)Z_u\big|_{\overline{SOC}(\varepsilon;s)}-\frac{1}{\varepsilon}\left(\left(\partial c^L/\partial x\right)\Big|_{\overline{STAT}(\varepsilon;s)}-\left(\partial c^L/\partial x\right)\Big|_{\overline{SOC}(\varepsilon;s)}\right)$. □

D. Proof of Proposition 3

The first-order conditions for the socially optimal outcome are given by $\left(f'(u)-w\right)\varepsilon-\tau_u^{DynStat}(t,\varepsilon)-\tau_u^{DYN}=0$, and $-\left(w^{fix}\right)'\varepsilon-\tau_x^{DynStat}(t,\varepsilon)\ -\tau_x^{DYN}=0$ where $\tau_u^{DynStat}$ and $\tau_x^{DynStat}$ indicate taxes on the variable input and on the employed technology x respectively. These taxes take account of the costs of air pollution at location ε but also of the existing tax $\tau_u^{DYN}=\frac{1}{\varepsilon}\gamma Z_u$ on the CO_2 emissions in the atmosphere. The first-order conditions of the first-best outcome are recovered if the taxes are set as $\tau_u^{DynStat}(t,\varepsilon)=\frac{1}{\varepsilon}\left(\left(\partial c^L/\partial u\right)\Big|_{\overline{SOC}(\varepsilon;s)}+\eta(t)Z_u\big|_{\overline{SOC}(\varepsilon;s)}-\gamma(t)Z_u\big|_{\overline{DYN}(\varepsilon;s)}\right)$ and $\tau_x^{DynStat}(t,\varepsilon)=\frac{1}{\varepsilon}\left(\left(\partial c^L/\partial x\right)\Big|_{\overline{SOC}(\varepsilon;s)}+\eta(t)Z_u\big|_{\overline{SOC}(\varepsilon;s)}-\gamma(t)Z_u\big|_{\overline{DYN}(\varepsilon;s)}\right)$. □

E. Proof of Proposition 4

We compare the agents' tax burden of noncoordinated policies, i.e., $\tau_{u_{jk}}^{STAT},\tau_{x_{jk}}^{STAT},\tau_{u_{jk}}^{DYN},\tau_{x_{jk}}^{DYN}$ with the tax burden of coordianted policies, ie., $\tau_{u_{jk}}^{SOC},\tau_{x_{jk}}^{SOC}$. For the case of the input tax we obtain that $\tau_u^{STAT}+\tau_u^{DYN}=\frac{1}{\varepsilon}\left(c_u^L\big|_{\overline{STAT}(\varepsilon,s)}+\gamma Z_u\big|_{\overline{DYN}(\varepsilon,s)}\right)>\frac{1}{\varepsilon}\left(c_u^L+\eta Z_u\right)\Big|_{\overline{SOC}(\varepsilon,s)}=\tau_u^{SOC}$ if the technology is identical for three tax regimes. Similarly, we obtain that $\tau_x^{STAT}+\tau_x^{DYN}=\frac{1}{\varepsilon}\left(c_x^L\big|_{\overline{STAT}(\varepsilon,s)}+\gamma Z_x\big|_{\overline{DYN}(\varepsilon,s)}\right)<\frac{1}{\varepsilon}\left(c_x^L+\eta Z_x\right)\Big|_{\overline{SOC}(\varepsilon,s)}=\tau_x^{SOC}$.

For $c^L=\left(\left(\beta_0-\beta_{1(x)}\right)u\varepsilon\left(1+0.001*s\right)\right)^2$ we get from the f.o.c. $f'(u)-w=c_u^L$ that

$$\frac{du}{dx}=\frac{-\frac{1}{\varepsilon}c_{ux}^L}{f''(u)-\frac{1}{\varepsilon}c_{uu}^L}=\frac{4\varepsilon\left(1+0.001s\right)^2u\left(\beta_0-\beta_1(x)\right)\beta_1'(x)}{f''(u)-2\varepsilon\left(1+0.001s\right)^2\left(\beta_0-\beta_1(x)\right)^2}<0.$$

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