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Regulation of location-specific externalities*

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Abstract

In this paper, we study regulation of externalities involving many small-scale polluters, where the damages from emissions depend on the polluters' locations. Examples include nutrient and pesticide emissions from farms, particulate emissions from vehicles and home heating units, emissions of hazardous chemical compounds from small business etc. With such emission problems, regulatory authorities often apply a combination of firm-level, possibly differentiated standards for 'cleaner' technologies, and market-level, undifferentiated dirty input regulations. We establish general principles for how such regulations should be designed and combined. We find that the optimal regulation design crucially depends on the type of cleaner technologies available to polluters. If these are 'emission capturing', optimal technology standards encourage the use of cleaner technologies in both high and low damage areas, while if they are 'input displacing', optimal technology regulation encourages cleaner technologies in high damage areas, but discourages their use in low damage areas. Regulation should always discourage the use of dirty input and the optimal regulation intensity may be substantial, particularly if the available cleaner technologies are input displacing.

JEL: H23, Q58, D62
Keywords: Location-specific externalities, clean technologies, regulation, policy

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1. Introduction

The environmental and health impacts of pollution are substantial and polluters are subject to extensive regulation in most high and medium-income countries. An important subset of such regulation problems concerns the regulation of many small-scale polluters where the damage resulting from emissions varies with the polluters' locations. Examples include nutrient and pesticide emissions from farms, particulate emissions from vehicles and home heating units, emissions of particulates and hazardous chemical compounds from smaller firms, etc. In practice, emissions from small-scale polluters are often regulated indirectly through technological standards and/or restrictions on the use of the 'dirty' inputs that contribute to the pollution.

In the following, we establish general principles for how such regulations should be designed and combined. Specifically, we consider externality problems where the damage per unit of emission arising from the use of a dirty input differs across polluters. We assume that the instruments the regulatory authorities can use are technology standards or other technology incentives that can be differentiated across polluters and restrictions on dirty input use that cannot. Examples of the first type of instruments are emission or engine standards for vehicles and home heating units, technical standards and BAT requirements for production equipment, standards for and subsidies to fertilizer conserving farming technologies and crops etc. Such technology standards can be and often are differentiated between polluters with tougher standards being applied in populated arias or close to vulnerable eco-systems. Examples of the latter are taxes on, bans of or quantitative restrictions on the harmful substance content in inputs such as additives in fuel, active compounds in pesticides and chemicals etc. Such regulations are difficult to differentiate between individual polluters and are typically applied uniformly. Our question is: How intensively should each of these regulatory instruments be used in order to maximize welfare?

Even though this type of regulation problem is common in practice, it has not been previously studied to our knowledge. A number of papers have investigated emission regulation through input-output taxes, e.g., Ayres and Kneese (1969), Holterman (1976), Bohm (1981), Larsson et al. (1996), Claassen and Horan (2001), Hansen and Hansen (2014). Part of this literature identifies situations where 'mass balance relationships' make it possible to measure emissions indirectly and then implement Pigouvian incentives through, for example, deposit-refund systems for bottles, batteries and persistent substances. Other papers have considered various aspects of technology regulation alone, e.g., Georg et al. (1992), Wayne (2003), Sengubta (2012), Klier (2016). Finally, a number of papers consider the interaction of different instruments in the regulation of emissions, e.g., Goulder et al. (1999), Christiansen and Smith (2015), and Abrell and Rausch (2017). The existing papers that are closest to ours are Christiansen and Smith (2015), who investigate optimal combinations of technology regulation and taxes on emissions, and Claassen and Horan (2001), who consider uniform input regulation as a second best policy for emission regulation. However, we do not know of any contributions that investigate and develop general guidelines for how to combine differentiated regulation of production technology and uniform regulation of inputs.

We develop a formal model of location-specific externalities, where the profit as well as the emission of each polluter is assumed to depend on the amount of 'dirty' input used and on the quality or 'cleanness' of pollution reducing technology installed. Formally authorities can implement uniform disincentives for dirty input use and differentiated incentives for installation of cleaner technology. We derive principles for how *intensive* the regulation of dirty input use and technology should be, and in particular for how technology regulation should be differentiated across polluters. Installing cleaner technology can reduce emissions through two, fundamentally different mechanisms: One is *emission capturing*, whereby the emission resulting from a given amount of dirty input is reduced (as when an end-of-pipe filter is installed). The other is *input displacement*, which reduces emissions by reducing the use of dirty input in production (this could be the installation of a production technology that makes it possible to substitute some of the dirty input with a corresponding cleaner input). Generally, cleaner technologies involve both types of effects, but their relative importance can vary substantially.

We find that the optimal regulation design crucially depends on the relative importance of the emission capturing and the input displacing effects of the cleaner technologies available to the polluting industry: First, even though we assume that technology regulation can be finely differentiated to reflect local damage levels and input regulation cannot, optimal regulation generally implies that uniform dirty input regulation should be applied. Furthermore, the intensity of dirty input regulation may well be of substantial size, particularly if the available cleaner technologies are mainly of the input displacing type. Second, when the available cleaner technologies are mainly of the emission capturing type, the optimal technology regulation unambiguously encourages the use of cleaner technologies for all damage levels (although with different intensities), while if the available technologies are mainly of the input displacing type, optimal technology regulation encourages cleaner technologies in high damage areas, but *discourages* their use in low damage areas.

Our results apply to the welfare maximization problem where authorities are restricted to using the two indirect regulation instruments we consider. Clearly, if the emissions we study could be measured and regulated directly, it would be possible to implement the standard Pigouvian tax recommendation, which would ensure the first best solution to the regulation problem. The reason why authorities choose to regulate emissions *indirectly* through technology standards and dirty input regulation may be that it is simply not feasible in practice to measure and regulate emissions directly. This is certainly the case for some types of pollution such as nutrient and pesticide emissions from farms and particulate emissions from vehicles. In other cases, regulators may be reluctant to impose differentiated emission taxes not because of infeasibility, but for reasons of income distribution or other political considerations. At any rate, since these indirect instruments are those actually used in practice, we believe that providing guidance on how they should be designed and combined if regulation is to be most efficient can provide a useful benchmark for regulators and other interested parties regardless of why regulators chose to limit themselves to these instruments.

In Section 2, we provide motivation for considering the particular regulation problem we study, in particular for the limited set of regulatory instruments allowed. Section 3 sets up the model formally, while in Section 4, we characterize optimal regulation under the allowed instrument set. Section 5 discusses the intuition behind the derived regulation principle and its implications for regulation in practice and Section 6 offers some overall conclusions.

2. The regulation problem considered: motivation

In this section, we present three fundamental features of the regulation problem we model and argue that these are typical of many real world externality problems involving small-scale polluters.

First, as mentioned above, we consider problems of *location-specific externalities* where the 'damage level', i.e., the marginal external cost per unit of emission, varies across polluters, but does not depend on the level of emission at the location or total emission.[1] In many cases, emissions in densely populated areas or close to particularly valuable or sensitive ecosystems are more harmful than emissions in less densely populated areas or far from important eco-systems. For instance, the damage caused by nutrient and pesticide emissions from farms typically depends on how close to the affected ecosystem the field is located. Likewise, the external health costs from air pollutants like NOx, CO, SO_2 and fuel exhaust particulates from vehicles, households and firms, typically depend on how close the polluter is to populated areas. This is also the case for emissions of hazardous chemical compounds and residues from industrial production, auto repair shops, etc.

Second, we consider problems where *the damage level of each polluter is known by the regulator*. This is the case, at least to some extent, for many of the types of emissions mentioned above. For example, in Denmark and other countries, authorities use high resolution air pollution emission-decimation models of NOx, SO_2, CO and particulates to identify geographical variation in the health effects of emissions.[2] Similarly, for water pollution, emission-decimation models are used to construct 'retention maps' that identify geographical variation in the environmental damage caused by nutrient emissions at the field level.[3]

Third, we consider problems where authorities apply a constrained set of regulatory instruments. Specifically, *authorities do not regulate emissions directly*. Instead *they can impose 'cleaner production' standards (or create other incentives) for the*

[1] Each small polluter is assumed to contribute only marginally to the total emission at the receptor level, so marginal external cost will be given relative to individual emissions. With respect to total emission, we implicitly assume that over the relevant range (from no regulation to optimal regulation) marginal damage is approximately constant.
[2] See, e.g., Brandt et al. (2012).
[3] See, e.g., Kristensen et al. (2008) and Højbjerg et al. (2015).

technologies used by polluters, and *these can be differentiated across polluters*. Furthermore, *they can impose undifferentiated market level regulation of dirty input use*. Authorities typically apply one or both of these indirect instruments instead of regulating emissions directly when they are faced with location-dependent externality problems emanating from by many small scale polluters. In the rest of this section we specify the instrument restrictions we assume and provide a number of real world examples to support our claim that these are realistic.

We assume that the regulator is able to observe the characteristics of each individual polluter's production technology that influence emissions (the type of furnace, smoke stack filtering or nutrient substituting technology, etc.), and we assume that the authorities are able to rank the technologies from which polluters can choose according to 'how clean they are' and impose technology requirements or incentives along the observed dimension. Because this characteristic of each polluter's technology can be observed, we assume that *technology regulation can be differentiated between polluters*, e.g., according to the damage level at the polluter's location.

This reflects how small-scale polluters are typically regulated in practice with polluting farms, firms, households and vehicles often being required to use 'cleaner' production technologies. European Union directives stipulate that industrial production processes in all EU member states use BAT (best available technology) in order to mitigate the emission of pollutants.[4] Similarly, the regulation of industrial production technologies is widely applied in the USA.[5] Furthermore, farms in most of Europe and the USA are subject to regulations specifying technology standards for the storage and application of animal manure and pesticides.[6] Vehicles in the EU and the USA are subject to emission standards that demand the use of catalytic converters and filters that reduce particulates, VOC, CO and NO_x emissions in exhaust fumes.[7]

All of these regulations require the use of technologies that are cleaner than those the polluters may otherwise have preferred to use. In many cases, because installation of

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[4] See, e.g., the EU Industrial Emissions Directive, which can be found at: http://ec.europa.eu/environment/industry/stationary/index.htm.

[5] See, e.g., the US Clean Air and Water Acts: https://www.epa.gov/clean-air-act-overview/plain-english-guide-clean-air-act and https://www.epa.gov/laws-regulations/summary-clean-water-act).

[6] See, e.g., the EU Water Framework Directive: http://ec.europa.eu/environment/water/water-framework/index_en.html and US agricultural regulations: https://www.epa.gov/agriculture/agriculture-laws-and-regulations-apply-your-agricultural-operation-farm-activity.

[7] See, e.g., http://eurlex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2007:171:0001:0016:EN:PDF.

the required technology can be verified by inspection, controlling compliance is feasible even when regulation is differentiated across polluters. Indeed, differentiation of technology regulation according to damage level is common: In agricultural regulation, the use of set aside, uncultivated, unfertilized and/or pesticide-free boundary zones, catch crops and other crop rotation requirements can be, and sometimes are, differentiated according to the damage nutrient emissions cause . Air pollution regulations are often tougher for households and firms in populated areas, for instance, demanding the use of low emission burners and filtering, or stipulating that households and firms are connected to district heating in cities. Furthermore, regulations often stipulate tougher emission standards for vehicles driving in inner cities than elsewhere, and in many cities electric vehicles are subsidized through being exempt from city tolls, being allowed to park for free and to drive in bus and taxi lanes, etc.

It is also assumed that *authorities do not differentiate regulation of input use between the individual polluters*. In contrast to technology regulation, input regulation is often difficult to differentiate effectively between polluters because of the risk of 'illicit trade' in inputs between polluters. Fertilizer, pesticides, fuel and other inputs are easy to transport, which makes it difficult for authorities to control transactions between polluters. If complied with, differentiated input regulation (e.g., an input tax reflecting the damage level at each individual the polluter's location) would likely create differences in the marginal profit of input (before tax) across polluters, thereby making such transactions profitable, which would undermine the intended differentiation.[8] However, we assume that *authorities can impose uniform regulation on dirty inputs, which applies to all polluters* by, e.g., imposing a uniform sales tax on dirty inputs or an input quota system, where the quote price provides a uniform disincentive to use the input.

Indeed, uniform taxes and regulations of 'dirty' inputs are applied in many cases involving small-scale polluters.[9] Vehicle and heating fuels are taxed and their

[8] In many cases, evasion of damage level differentiated input regulation (e.g., a tax) would not even require transactions between different polluters. For instance, a tax on fuel differentiated according to where the vehicle is driven would be evaded if the owner bought fuel in a low tax area, but drove the vehicle in a high tax area. Likewise, many farmers own fields with different damage levels with respect to nutrient run-off from fertilizer. Therefore, they would be able to evade a damage level differentiated tax on Nitrogen by 'trading with themselves'.

[9] See, e.g., OECD (2001) and OECD (2010).

specifications and additives are regulated in many US and European states, while taxes, quotas and other general regulations are imposed on farm inputs such as fertilizer and pesticides in many European countries.[10]

The fact that authorities often apply indirect regulation of production technologies and dirty inputs rather than direct regulation of emissions may at first seem surprising, because this rules out the use of classical Pigouvian emission taxes that would, in theory, be preferable. The reason may, as already noted, be that measurement of the relevant emissions is infeasible or prohibitively expensive. For instance, it is not feasible to track and measure the amount of particulates from a specific source, say a car or a burner in a house or firm, that reaches a city miles away, or the amount of nutrients from a particular farm or field that reaches a certain inlet on the coast. In other cases the reason may be that direct (and differentiated) regulation of emissions is considered politically infeasible. A policy that induces or mandates certain technologies may be less unpopular than one that taxes or constrains emissions. Clearly, if direct measurement and regulation of emissions are feasible at reasonable cost differentiated emission taxes would often be the preferred instrument. However, if regulators, for whatever reason, are prevented from using such taxes it may be useful for them to know the (second) best way to design the regulations that they are able to use.

The purpose of this paper is exactly to establish principles for the best possible regulation given the three assumed features of the regulation problem, i.e. to derive the optimal combination of regulation intensities for the *general* regulation of dirty inputs and the *differentiated* (damage level dependent) regulation of clean technologies. We proceed by setting up our model formally.

[10] Regulators do frequently differentiate between polluters by specifying that the use of certain inputs is allowed for some polluters, but not for others. For example, only firms or farms that fulfill certain standards or are located far from populated or sensitive areas are licensed to use certain hazardous inputs. However, restricting firms to technologies that do not use certain inputs is, according to our terminology, technology regulation. Such regulation can often be effectively controlled by periodic inspection. According to our terminology, differentiated input regulation is when the use of the dirty input is allowed, but regulation attempts to differentiate effective input prices or volumes across polluters. This is much more difficult to control and is not common in practice.

3. The regulation problem considered: model

We consider an industry with a continuum of firms each earning profit from a production process that involves the use of a 'dirty' input that results in damaging emissions. Each firm is indexed by its damage level $i \in [0,1]$, which is the marginal external cost of emission at the location of the firm and assumed to be constant (and thus independent of the firm's own emission) over the span of total emissions considered. The highest damage level is normalized to one. We let $q(i)$ be a density function that describes the distribution of firms according to their damage level, and we denote by E the expectation (mean) operator with respect to *i*. It follows that damage from an additional unit of industry emission distributed across locations in proportion to the number of firms is $E(i) \equiv \int_0^1 iq(i)\,di.$[11]

We let $g_i \geq 0$ denote the amount of dirty input used by firm *i*. Each firm has access to various production 'technologies' and chooses its production technology from a common set which is available to all firms in the industry. Each of these technologies is characterized by an index value *h*, which ranks the technologies so that $h = 0$ is the 'dirtiest' technology and $h = \infty$ is the 'cleanest'. We let $h_i \geq 0$ denote the technology type chosen by firm *i*.

The profit function of the representative firm at location *i* is $\Pi^i(g_i, h_i)$, which can be thought of as a reduced form where other inputs, e.g., labor, are used at profit maximizing levels. Our formulation allows profit functions to vary with damage level as indicated by superscript *i* on Π. It is important to note that h_i is not to be thought of as an amount of input, but as a quality index indicating the 'cleanness' of the applied

[11] Strictly speaking, in the model there is one representative firm for each damage level *i* and $q(i)$ is the relative weight of this firm in the industry. Since there will always be some, possibly small difference between the damage levels of any two firms, this is not really a limiting assumption.

technology. For example, an increase in the quality index h_i for given g_i may well reduce profit.[12]

The emission from firm *i* given g_i and h_i is denoted by $F^i(g_i, h_i)$, so the total damage caused by emission from firm *i* is $F^i(g_i, h_i)i$.

The social welfare contribution of a firm *i* is economic surplus minus external cost:

$$W^i(g_i, h_i) \equiv \Pi^i(g_i, h_i) - F^i(g_i, h_i)i \quad (1)$$

while the welfare contribution of the whole industry is:

$$W \equiv \int_0^1 W^i(g_i, h_i)q(i)di \quad (2)$$

We impose standard 'concavity' assumptions on the firms' profit functions, both with respect to dirty input use, $\Pi^i_g(0, h_i) = \infty,\ \Pi^i_{gg}(g_i, h_i) < 0,\ \Pi^i_g(\infty, h_i) < 0,$ and with respect to the level of technology, $\Pi^i_h(g_i, 0) = \infty,\ \Pi^i_{hh}(g_i, h_i) < 0,\ \Pi^i_h(g_i, \infty) < 0$ (where subscript *g* indicates partial derivative with respect to g_i etc.). The latter three conditions state that the marginal profit from choosing a cleaner technology may be positive for low index values (and will be so for the 'dirtiest' technologies with index value close to 0), that the marginal profit is decreasing in h_i, and that there is some level of technology cleanness above which the marginal profit of cleaner technology gets negative. The stated assumptions are technical and ensure (together with assumption (4) below) the existence and uniqueness of interior solutions to each firm's problem of choosing an optimal amount of input and an optimal level of technology.

For the emission function, we impose the natural assumption, $F^i_g(g_i, h_i) > 0.$ Furthermore, since the *h*-index indicates a ranking of increasingly cleaner technologies,

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[12] One can think of the profit function as $\Pi^i(g_i, h_i) = y^i(g_i, h_i) - p_g g_i - c^i(g_i, h_i),$ where y^i is a (reduced form) production function, p_g is the price of the dirty input, and $c^i(g_i, h_i)$ is the cost associated with h_i given g_i. In this case, $\partial y^i / \partial h_i > 0$ would not be an appropriate assumption in all cases.

it is natural to think of emissions as non-increasing (and possibly decreasing) in h_i and of the marginal profitability of the dirty input as non-increasing (and possibly decreasing) in h_i. Therefore, we assume that for all *i*, g_i and h_i:

$$F_h^i(g_i, h_i) \le 0 \tag{3}$$

$$\Pi_{gh}^i(g_i, h_i) \le 0 \tag{4}$$

Condition (4) implies that if a firm is induced to use a cleaner technology, it will not be profitable for it to use more dirty input, but generally less. We consider assumptions (3) and (4) as natural requirements for a ranking of technologies representing cleanness.[13]

In our model, all firms use the same dirty input and have access to the same production technologies whose environmental effects can be captured by a one-dimensional cleanness index. These features are, of course, simplifications, but still the model is versatile and allows a continuum of different types of technologies.

At one end of this continuum we have purely *emission capturing*, end-of-pipe technologies that reduce emissions resulting from a given level of use of dirty input without affecting the firm's incentive to use the dirty input. These technologies are characterized by $F_h^i(g_i, h_i)$ and $F_{gh}^i(g_i, h_i)$ being strictly negative (and possibly of considerable numerical size) for relevant (g_i, h_i), so that cleaner technology gives an absolute reduction of emission as well as reduced marginal emissions from input use (as would be the case, e.g., if a certain fraction of emission is captured), and $\Pi_{gh}^i(g_i, h_i)$ being equal to zero everywhere, i.e.:

$$\begin{aligned} &F_h^i(g_i, h_i) << 0,\ F_{gh}^i(g_i, h_i) << 0 \\ &\Pi_{gh}^i(g_i, h_i) = 0 \end{aligned} \tag{5}$$

[13] Since h_i is not an amount of input that can be substituted by g_i, but a quality of the chosen technology, an assumption of a strictly positive second cross derivative, which would be standard in production theory with several substituting inputs, is not appropriate here.

Examples of mainly emission capturing technologies are filters, which are installed in firms' chimneys or in vehicles etc. to capture a fraction of the damaging substances from emissions, or wetlands established in agriculture to prevent a fraction of lost nutrients leaching into vulnerable waters.

At the other end of the technology continuum are purely *input displacing* technologies, which do not affect the emission resulting from the use of a given amount of dirty input, but induce the firm to use less of this input. These are characterized by $F_h^i(g_i, h_i)$ and $F_{gh}^i(g_i, h_i)$ being equal to zero everywhere, and $\Pi_{gh}^i(g_i, h_i)$ being strictly negative (and possibly of considerable numerical size) for relevant (g_i, h_i), i.e.:

$$\begin{aligned} &F_h^i(g_i, h_i) = F_{gh}^i(g_i, h_i) = 0, \\ &\Pi_{gh}^i(g_i, h_i) << 0 \end{aligned} \qquad (6)$$

Examples of mainly input displacing technologies abound in the agricultural sector and include the planting of crops that require less and/or absorb more fertilizer, the use of technologies for precise manure spreading and the planting of catch crops.[14]

Often the clean technologies available to an industry will both reduce emission per unit of dirty input used and induce less use of the dirty input thus having both an emission capturing and an input displacing effect. For such combined technologies, all of $F_h^i(g_i, h_i)$, $F_{gh}^i(g_i, h_i)$ and $\Pi_{gh}^i(g_i, h_i)$ will be strictly negative (and of considerable size). An example of this is an end of pipe technology where operating costs depend on the amount of the dirty input used such as filters based on costly chemical reduction techniques where filter replacement and maintenance costs depend on the amount of pollutant filtered.[15]

In line with the discussion in Section 2, we make the following assumptions regarding the information upon which authorities base their regulation: They are able to observe the total amount of the dirty input used by the industry and, therefore, can

[14] A catch crop takes up some of the fertilizer, which is lost by the main crop after which it is ploughed back into the soil so that the fertilizer can be reused by the next main crop, thereby saving on fertilizer.
[15] Strictly speaking, one could imagine 'clean' technologies that are, e.g., highly emission capturing and, at the same time, slightly dirty input inducing. However, this seems an unusual special case and, therefore and for the sake of simplicity, we do not consider such technologies.

impose uniform regulation of input use that applies to all firms, e.g., a uniform tax on input sold in the primary market or quantitative restrictions with the same effect (which could be a cap and trade system). They cannot observe and do not base regulation on individual firms' emissions, $F^i(g_i, h_i)$, or individual firms' use of the dirty input, g_i. and thus cannot prevent redistribution of dirty input between firms if such redistribution is advantageous. However, they can observe and base regulation on the individual firm's level of technology, h_i, and its damage level, *i*.

4. Optimal (second best) regulation

Let a 'plan' be a list of decision variables for each firm, $\left(h_i, g_i\right)_{i\in[0,1]}$. The feature that redistribution of dirty input between firms (if advantageous) cannot be prevented implies a restriction on which plans could possibly be achieved. These are plans for which the marginal profitability of the dirty input is the same for all firms, i.e.:[16]

$$\text{There is a } z \geq 0, \text{ such that for all } i: \ \Pi_g^i(g_i, h_i) = z \qquad (7)$$

A 'second best' plan is one that maximizes *W* defined in (2) over all plans that satisfy (7). In the following we first characterize second best plans and then turn to how they can be implemented by appropriate regulation. The characterization part has two steps: first we derive a best plan given *z*, then we find the best *z*.

The condition in (7) implicitly defines g_i as a function of h_i and *z* for each firm *i*, i.e., $g_i = g^i\left(h_i, z\right)$, where $\Pi_g^i(g^i\left(h_i, z\right), h_i) = z$. The sensitiveness of input use with respect to the clean technology index h_i and the required marginal profitability *z* according to this function will be of importance in the following. By implicit differentiation:

[16] Note that it is without limitation in (7) to assume $z \geq 0$, since if $z < 0$, profit can be increased *and* emissions reduced by reducing g_i, so $z < 0$ cannot be optimal.

$$g_h^i\left(h_i, z\right) = -\frac{\Pi_{gh}^i\left(g^i\left(h_i, z\right), h_i\right)}{\Pi_{gg}^i\left(g^i\left(h_i, z\right), h_i\right)} \le 0 \tag{8}$$

$$g_z^i\left(h_i, z\right) = \frac{1}{\Pi_{gg}^i\left(g^i\left(h_i, z\right), h_i\right)} < 0 \tag{9}$$

From (1), the social welfare contribution of firm *i* for given *z* (taking the relationship $g_i = g^i\left(h_i, z\right)$ into account) is a function of h_i, z and *i*:

$$W^i\left(g^i\left(h_i, z\right), h_i\right) \equiv \Pi^i(g^i\left(h_i, z\right), h_i) - F^i(g^i\left(h_i, z\right), h_i)i \tag{10}$$

The first order condition for maximizing $W^i(g^i(h_i, z), h^i)$ with respect to h_i (which we assume to be necessary and sufficient for a unique, interior solution $h_i > 0$), is

$$W_g^i(g^i\left(h_i, z\right), h_i)g_h^i\left(h_i, z\right) + W_h^i(g^i\left(h_i, z\right), h_i) = 0 \tag{11}$$

Equation (11) can be traced back to the Π^i- and F^i-functions by using (10):

$$\begin{aligned}&\left[\Pi_g^i(g^i\left(h_i, z\right), h_i) - F_g^i\left(g^i\left(h_i, z\right), h_i\right)i\right]g_h^i\left(h_i, z\right) + \\ &\Pi_h^i\left(g^i\left(h_i, z\right), h_i\right) - F_h^i\left(g^i\left(h_i, z\right), h_i\right)i = 0\end{aligned} \tag{12}$$

This is a marginal condition stating that for each firm *i*, the marginal profit of a change in technology, which is accompanied by the adjustment in inputs required to maintain the current level of the marginal profitability of input, $\Pi_g^i g_h^i + \Pi_h^i$, must equal the marginal damage of the same change in technology caused by the resulting change in emissions, $\left(F_g^i g_h^i + F_h^i\right)i$.

Equation (11) implicitly defines the socially optimal h_i for firm *i* given *z* as a function of *z* and *i*: $h_i = h^i(z, i)$. Inserting this into $W^i\left(g^i\left(h_i, z\right), h_i\right)$ gives the social welfare contribution of firm *i* (at the socially optimal technology given *z*) as a function of *z* and *i:*

$$\hat{W}^i(z,i) \equiv W^i\left(g^i\left(h^i(z,i),z\right),h^i(z,i)\right) \tag{13}$$

Differentiating (13) with respect to *z* gives:

$$\begin{aligned}\hat{W}_z^i(z,i) &= \underbrace{\left(W_g^i g_h^i + W_h^i\right)}_{=0} h_z^i + W_g^i g_z^i \\ &= W_g^i(g^i\left(h^i(z,i),z\right),h_i)g_z^i\left(h^i(z,i),z\right)\end{aligned} \tag{14}$$

Here it was used that by (11), the effects in (14) going through $h_i = h^i(z,i)$ cancel out as indicated (the envelope theorem). From (10) it follows that:

$$W_g^i = \Pi_g^i - F_g^i i \tag{15}$$

Inserting this and $\Pi_g^i = z$ (from (7)) into (14) we obtain:

$$\hat{W}_z^i(z,i) = \left[z - F_g^i(g^i\left(h^i(z,i),z\right),h^i(z,i))i\right]g_z^i\left(h^i(z,i),z\right) \tag{16}$$

This is the change in the welfare contribution from firm *i* per unit increase in the common marginal profitability of the dirty input, *z*. From (2) and (13), the welfare contribution of the whole industry as a function of *z* (conditional on the application of the best available technology for each firm given *z*) is:

$$W(z) \equiv \int_0^1 \hat{W}^i(z,i)q(i)di \tag{17}$$

Differentiating (17) and then inserting from (16) gives the first order condition for maximizing welfare $W(z)$ with respect to *z*:

$$\begin{aligned}\frac{\partial W(z)}{\partial z} &= \int_0^1 \hat{W}_z^i(z,i)q(i)di \\ &= \int_0^1 \left[z - F_g^i(g^i\left(h^i(z,i),z\right),h^i(z,i))i \right] g_z^i\left(h^i(z,i),z\right)q(i)di = 0\end{aligned} \tag{18}$$

which can be rewritten as:

$$zE\left[g_z^i\left(h^i(z,i),z\right)\right] - E\left[F_g^i(g^i\left(h^i(z,i),z\right),h_i)g_z^i\left(h^i(z,i),z\right)i\right] = 0 \tag{19}$$

Hence, the first order condition for the optimal uniform marginal profitability *z* implies:

$$z = E\left[iF_g^i \frac{g_z^i}{E\left[g_z^i\right]}\right] \tag{20}$$

Using the definition of covariance (the mean of the product of two random variables equals the product of the means plus the covariance) we can reformulate (20) in a way that will allow for easier interpretation (as explained in the next section). Letting the 'random variables' be *i* and $F_g^i g_z^i / E\left[g_z^i\right]$, (20) can be rewritten as:[17]

$$z = E[i]E\left[F_g^i \frac{g_z^i}{E\left[g_z^i\right]}\right]\left(1 + \operatorname{cov}\left[\frac{i}{E[i]}, \frac{F_g^i g_z^i}{E\left[F_g^i g_z^i\right]}\right]\right) \tag{21}$$

where the covariance is between the normalized damage levels, $i / E[i]$, and the normalized marginal emissions from additional dirty input use as resulting from a change in *z*, $F_g^i g_z^i / E[F_g^i g_z^i]$.

In (20) and (21), $F_g^i = F_g^i(g^i\left(h^i(z,i),z\right),h^i(z,i))$ and $g_z^i = g_z^i\left(h^i(z,i),z\right)$, so both sides of each equation are functions of *z* alone. We assume that (20) or (21) determines

[17] See Appendix A for the details.

the optimal z^* uniquely. Since the right-hand side of (20) or (21) only involves strictly positive components, this will generally be strictly positive, $z^* > 0$.

A second best outcome is a plan $(h_i^*, g_i^*)_{i\in[0,1]}$, which, for the z^* that solves (20) (or (21)), fulfils the condition in (7) as well as the marginal condition (12), that is:

$$\Pi_g^i(g_i^*, h_i^*) = z^* \quad \text{and} \tag{22}$$

$$\left[z^* - F_g^i\left(g_i^*, h_i^*\right)i\right] g_h^i\left(h_i^*, z^*\right) + \Pi_h^i\left(g_i^*, h_i^*\right) - F_h^i\left(g_i^*, h_i^*\right)i = 0 \tag{23}$$

We assume that (20) (or (21)) and (22) and (23) determine $(h_i^*, g_i^*)_{i\in[0,1]}$ uniquely.

Next we turn to the implementation of the second best plan. Formally, we consider a uniform tax rate, *t*, on input and firm-specific taxes rates, s_i, on each firm's technology index level, where a negative value of s_i corresponds to a subsidy to technology cleanness. These 'tax rates' should be interpreted broadly as *regulation intensities*, indicating the size of the incentive corrections that regulation should result in irrespective of the types of regulation actually used to implement them. In practice, technology regulation often takes the form of minimum standards or mandate of the use of specific technologies. In that case our optimal 'tax rates' indicate the optimal pattern of regulatory intensities and differentiation across firms that the regulatory instrument should ideally achieve.

The first order conditions for maximizing profit after tax, $\Pi^i(g_i, h_i) - tg_i - s_i h_i$, are:

$$\Pi_g^i\left(g_i, h_i\right) = t \quad \text{and} \tag{24}$$

$$\Pi_h^i\left(g_i, h_i\right) = s_i \tag{25}$$

Hence, if one sets *t* equal to the z^* defined by (20) or (21) and:

$$s_i = \left[F_g^i\left(g_i^*, h_i^*\right)i - z^*\right] g_h^i\left(h_i^*, z^*\right) + F_h^i\left(g_i^*, h_i^*\right)i \tag{26}$$

the conditions (24) and (25) become equivalent to (22) and (23). Thus, regulation by a uniform tax rate $t = z^* > 0$ as given by (20) or (21) on the dirty input, and firm-specific (possibly negative) taxes s_i as given by (26) on clean technologies will implement the second best plan. It is obvious from (26) that generally $s_i \neq 0$. In general, therefore, both uniform input taxes and differentiated technology taxes must be applied to implement the second best outcome.

Because of the way we have derived optimal regulation, we have not only found the best possible combination of uniform regulation of the dirty input and targeted regulation of clean technology, but we have also shown that this regulation gives the best outcome that can be obtained when redistribution of input cannot be prevented, i.e., given that the marginal profitability of input must be the same everywhere.

As noted above, the second best 'tax' solution consisting of the optimal *t* and s_i should be interpreted as *regulation intensities,* indicating the size of the incentive corrections that ideally should be generated irrespective of the specific types of regulation used by the authorities. The regulation principle we have derived can thus provide a benchmark that authorities can measure against irrespective of the specific regulatory instruments they use.

5. Intuition behind and implications of the regulation principle

In this section, we first discuss the intuition behind the second best regulation principle given by (20) or (21) and (26). We then illustrate its implications when the available clean technologies are either purely emission capturing or purely input displacing. Finally we discuss its applicability for regulation in practice.

Intuitive explanation of the regulation principle

As a benchmark, we first characterize a 'first best' outcome and hypothetical implementation of this. A first best plan maximizes $W^i(g_i, h_i)$ for each firm separately. The first order conditions for this are from (1), $\Pi^i_g(g_i, h_i) = F^i_g(g_i, h_i)i$ and $\Pi^i_h(g_i, h_i) = F^i_h(g_i, h_i)i.$ Assume that these determine the first best plan, $(h^o_i, g^o_i)_{i\in[0,1]}$, uniquely. With firm differentiated taxes on both input and technology cleanness by rates t_i and s_i, respectively, the first order conditions for maximizing net of tax profits, $\Pi^i(g_i, h_i) - t_i g_i - s_i h_i$, would be $\Pi^i_g(g_i, h_i) = t_i$ and $\Pi^i_h(g_i, h_i) = s_i$. Hence, setting the tax rates $t_i = F^i_g(g^o_i, h^o_i)i > 0$ and $s_i = F^i_h(g^o_i, h^o_i)i \leq 0$ would implement the first best outcome. These express perfectly 'Pigouvian' incentives: for each *i*, the differentiated input tax rate should equal the marginal external damage from additional input use, and the differentiated technology subsidy rate should equal the marginal external benefit from cleaner technology. If the available clean technologies do not have an emission capturing effect, $F^i_h(g^o_i, h^o_i) = 0$, then differentiated input taxes alone would implement the first best outcome.

When the input 'tax rate' cannot be differentiated and set equal to the marginal damage from input use for each individual firm, a Pigouvian intuition would suggest that the uniform tax rate *t* should equal an appropriate *mean* of the firms' marginal external damages from dirty input use. Our rule for the optimal tax rate derived from Equation (20), $t = E[i \cdot F^i_g \cdot g^i_z / E[g^i_z]]$, confirms this and tells exactly which mean is appropriate. Here, for each firm the marginal damage caused by use of the dirty input, $i \cdot F^i_g$, is multiplied by the relative 'tax sensitiveness' at the location, $g^i_z / E[g^i_z]$, and these products are then weighted by the relative number of firms at each location, $q(i)$. This creates all in all a mean of marginal damages equal to the total marginal damage resulting from a one unit increase in use of the dirty input for the industry as a whole, when the additional one unit of input is distributed across firms as it would be if induced by a uniform input tax reduction. This also explains why, in general, a strictly positive tax rate is required for optimal regulation: although technology regulation can be finely differentiated it will not, in general, reduce the marginal damages from input use to zero, and since the optimal uniform tax rate simply is the (tax sensitiveness weighted) mean of the marginal damages, this optimal tax rate will, in general, be strictly positive.

The alternative expression (21) for the optimal uniform tax rate also has an intuitive interpretation and may be of more operational use to regulators. The first factor on the right-hand side of (21), $E[i]$, is the mean damage resulting from an additional unit of emission distributed across firms according to their relative size, $q(i)$. The second factor, $E[F_g^i \cdot g_z^i / E[g_z^i]],$ is the mean of the firms' marginal emissions from input use arising from a tax decrease (resulting in a one unit increase in input use at the industry level). If the damage levels, *i*, and the marginal emissions resulting from a change in *z*, $F_g^i \cdot g_z^i / E[g_z^i],$ are not correlated, the product of the mean damage of emissions, $E[i],$ and the mean emission from a tax reduction, $E[F_g^i \cdot g_z^i / E[g_z^i]],$ will equal the mean of the product of damage levels, *i*, and marginal emissions, $F_g^i \cdot g_z^i / E[g_z^i],$ that is, $E[i] \cdot E[F_g^i \cdot g_z^i / E[g_z^i]] = E[i \cdot F_g^i \cdot g_z^i / E[g_z^i]],$ which is the optimal tax rate as expressed by (20). However, if the damage levels and marginal emissions resulting from *z* are correlated, one must correct for the covariance. This is achieved by the third factor on the right-hand side of (21), $1+\mathrm{cov}[i / E[i], F_g^i g_z^i / E[F_g^i g_z^i]]$. If there is a positive covariance, the input tax will reduce marginal emissions relatively more in high damage areas than in low damage areas. In this case, the correction factor is greater than one, which implies that the optimal tax rate on dirty input is greater than the product of mean damage and mean marginal emissions from dirty input use, $E[i] \cdot E[F_g^i \cdot g_z^i / E[g_z^i]].$ If the covariance is negative, the input tax tends to reduce marginal emissions relatively more in low damage areas. In this case, the correction factor will be less than one. Thus, the more effective the uniform tax is at reducing emissions where emissions are most harmful, the higher the tax rate should be.

Turning to the intuition behind Equation (26), the second term on the right-hand side, $F_h^i(g_i^*, h_i^*)i,$ is (weakly) negative and equal to the direct marginal effect on damage of a marginal increase in the technology index arising from the emission capturing effect of cleaner technology. Hence, from this effect in isolation cleaner technology should always be (weakly) promoted, and the greater the effect, the more intensely cleaner technology should be induced.

The first term on the right-hand side of (26), $[F_g^i(g_i^*, h_i^*)i - z^*]g_h^i\left(h_i^*, z^*\right)$, is (the negative of) the marginal social benefit of a marginal increase in the technology index as this arising from the input displacing effect of the cleaner technology. Here $g_h^i\left(h_i^*, z^*\right)$ is the displacement of dirty input caused by a marginal increase in the cleaner technology index, while $[F_g^i(g_i^*, h_i^*)i - z^*]$ is the social value per unit of this displacement. The social value of the marginal unit of input displaced is the resulting reduction in damage, $F_g^i(g_i^*, h_i^*)i$, minus the social cost of displacing one unit of dirty input, which equals the applied intensity of input regulation, z^*.[18] If input use were not regulated (corresponding to $z = 0$), the social cost of substituting the dirty input in production would be zero at the margin. However, because input use is regulated, the social cost of displacing one *more* unit is positive and equal to z^*. This implies that the marginal social value of the input displacing effect of cleaner technology is *negative* for firms where $F_g^i(g_i^*, h_i^*)i < z^*$ in optimum. Intuitively, the uniform input tax will be too high in low damage areas (where $F_g^i(g_i^*, h_i^*)i$ is relatively small) and it will, therefore, give too strong an incentive to adopt cleaner input displacing technology. This 'too strong' an incentive caused by the input tax should be taken into account and counteracted by the differentiated technology regulation applied to firms in low damage areas. In high damage areas, the corresponding incentive from the input tax will be too weak and should, therefore, be reinforced by the technology regulation. The sum of the emission capturing and the input displacing effects is the implied 'tax rate' on cleaner technology that second best regulation must reflect.

Implications of the regulation principle

To understand the implications of the regulation principle we have derived, we compare two industries that are identical except that one only has access to purely emission capturing technologies (so $\Pi_g^i(g_i, h_i)$ does not depend on h_i), while the other only has access to purely input displacing ones (so $F_g^i(g_i, h_i)$ does not depend on h_i). We assume that in an initial, unregulated state, the use of dirty input, g_i^u, the technology index, h_i^u, and the profits and emissions for each firm *i* are identical for the two industries at all locations. Furthermore, we assume that in the unregulated state, the mean marginal damage resulting from an additional unit of dirty input at the industry

[18] The social cost of displacing one unit of input, which is the social shadow price of input implied by the input regulation, must equal the marginal profitability of input.

level as given by expression (20), $z^u \equiv E[iF_g^i(g_i^u, h_i^u) g_z^i(h_i^u, 0) / E[g_z^i(h_i^u, 0)],$ is the same for the two industries.

We first consider input regulation assuming simplifying approximations of the profit and emission functions. Specifically, we assume that:

1) For all firms in both industries, marginal emissions are insensitive to input use, $F_g^i(g_i, h_i) = F_g^i(h_i)$, i.e., emissions are proportional to (linear in) input use.
2) For all firms in both industries, the input reductions from an increase in the tax rate, $g_z^i(h_i, z),$ are insensitive to h_i and z, that is, $g_z^i(h_i, z) = k_i.$[19]

These can be seen as natural approximations in the absence of specific knowledge about emission and input demand functions that suggests otherwise.

Under these assumptions, the mean marginal damage of the dirty input in the unregulated state is $z^u \equiv E\left[iF_g^i(h_i^u) k_i \ / E[k_i\ ]\right],$ while the optimal input tax rate (equal to the marginal damage of the dirty input at optimal regulation) is $z^* \equiv E\left[iF_g^i(h_i^*) k_i \ / E[k_i\ ]\right]$. For the industry with only input displacing technologies, $F_g^i(h_i)$ does not depend on h_i, which implies that $z^* = z^u.$ Although optimal technology regulation does reduce the use of dirty input this does not affect mean marginal damage under assumptions 1) and 2). For the industry with only emission capturing technologies, $F_g^i(h_i)$ depends on $h_i,$ such that a larger h_i implies a smaller $F_g^i(h_i).$ Since optimal technology regulation generally induces firms to adopt cleaner technologies, the marginal emissions $F_g^i(h_i)$ are smaller in the regulated than in the unregulated state, $F_g^i(h_i^*) < F_g^i(h_i^u).$ This implies that $z^* < z^u.$

[19] This second assumption holds (approximately) if, for example, the profit functions are (approximately) quadratic forms. In a standard case with quadratic profit functions, the industry that only has access to emission capturing technologies would have profit functions $\Pi^i(g_i, h_i) = -d^i h_i^2 / 2 - b^i g_i^2 / 2 + a^i g_i,$ where $a^i > 0, b^i > 0$ and $d^i > 0$ are parameters, and $\Pi_{gh}^i(g_i, h_i) = 0,$ while the industry that only has access to input displacing technologies would have $\Pi^i(g_i, h_i) = -d^i h_i^2 / 2 - b^i (g_i + h_i)^2 / 2 + a^i (g_i + h_i),$ where $\Pi_{gh}^i(g_i, h_i) = -b^i.$ The condition that marginal profitability of input use must equal the tax rate z would in the two cases lead to $g^i(h_i, z) = a^i / b^i - z / b^i,$ and $g^i(h_i, z) = a^i / b^i - h_i - z / b^i,$ respectively. In both cases, the tax response is $g_z^i(h_i, z) = -1 / b^i$, and thus independent of h_i and z.

This result for natural approximations suggests an overall tendency for the optimal tax on dirty input to be higher (and closer to the mean marginal damage in the absence of regulation), when the available technologies are mainly input displacing than when they are mainly emission capturing, other things being equal. This tendency does not hold in full generality, however.[20]

Next we consider the implications that the type of available technology has for the optimal technology incentives s_i, without imposing any functional form restrictions. For the industry with purely emission capturing technologies, $g_h^i(h_i, z) = 0$ and $F_h^i(g_i, h_i) < 0,$ so from (26) we have:

$$s_i = F_h^i\left(g_i^*, h_i^*\right)i < 0 \tag{27}$$

Here the appropriate tax rate is negative for all firms so that optimal technology regulation always induces or mandates the adoption of technologies that are cleaner than the firms would otherwise have found profitable, and the implied incentive should be stronger, the greater the marginal social benefit from cleaner technology at the location (i.e., the greater the damage level and the more sensitive emissions are to changes in technology). When clean technologies are purely emission capturing, the dirty input regulation does not induce any change in technology and, therefore, all firms must be induced to use cleaner technologies by the *technology* regulation.

For the industry with purely input displacing technologies, $g_h^i(h_i, z) < 0$ and $F_h^i(g_i, h_i) = 0,$ so from (26) we have:

$$s_i = \left[F_g^i\left(g_i^*, h_i^*\right)i - z^*\right]g_h^i\left(h_i^*, z^*\right) \begin{smallmatrix}<\\=\\>\end{smallmatrix} 0 \tag{28}$$

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[20] If, for example, the marginal emissions from dirty input were increasing in input use $(F_{gg}^i(g_i, h_i) > 0$ rather than $F_{gg}^i(g_i, h_i) = 0$ as assumed in 1) above), then the decrease of input use implied by optimal technology regulation when technologies are purely input displacing would cause the marginal damages from input use to fall and hence the optimal tax rate to be smaller than the mean marginal damage in the unregulated state. This could lead to the optimal input tax being lower for the industry with only input displacing technologies than for the industry with only emission capturing technologies.

where $s_i < 0$ for $F_g^i i > z^*$, and $s_i > 0$ for $F_g^i i < z^*$. Thus, for such an industry, optimal technology regulation should induce the adoption of technologies that are cleaner than those firms would have otherwise found profitable in areas where the marginal damage resulting from the dirty input use, $F_g^i\left(g_i^*, h_i^*\right)i,$ is greater than the social shadow price of input, z^*, induced by input regulation. However, in areas where the marginal damage is smaller than this shadow price, optimal technology regulation should induce the adoption of technologies that are *less clean* than firms would have otherwise found profitable. This may seem counter intuitive, but it follows directly from the intuition provided in the subsection above. When the available clean technologies are of the input displacing type, the input regulation gives all firms the same incentive to choose cleaner technology irrespective of their damage levels. Therefore, firms in low damage areas are induced to adopt technologies that are cleaner than what is efficient (input regulation is too tight in these areas). To some extent, the resulting welfare loss can be mitigated if the regulator uses technology regulation to induce the adoption of technologies that are less clean than firms would have otherwise found profitable in these areas.

Practical applicability of the regulation principle

To regulate exactly according to the derived regulation principle will often not be possible because regulators do not have all the required information about, e.g., the firms' profit and emission functions. Nevertheless, the regulation principles we have derived can be useful for outlining some guidelines for regulation in practice.

Regulators may often be able to identify the relative importance of input displacing effects verses emission capturing effects of the clean technologies available to an industry. For example, in the case of nitrogen leaching caused by fertilizer use, farmers can reduce emissions by planting crops that require less fertilizer and are better at absorbing nutrients, or by using more efficient manure spreading techniques, changing their crop rotation, establishing fertilizer-free boundary zones next to sensitive aquatic environments and planting catch and winter crops. All of these technologies are mainly of the input displacing type. For this regulation problem, our results indicate that a sizable tax on nitrogen (in fertilizer and animal feed) is likely to be appropriate, because the nitrogen emissions resulting from fertilizer use can be expected to be relatively large at the margin, when the emission capturing effect of the available cleaner technologies is small. Furthermore, in areas where nitrogen emissions result in relatively high levels of environmental damage, technology regulation should induce the adoption of crops and techniques that reduce fertilizer use even further than what is obtained by input taxation, whereas in areas where nitrogen emissions result in relatively low levels of environmental damage, technology regulations should induce the adoption of crops and techniques that increase fertilizer use compared to the levels induced by input taxation.

In other cases, the available technologies are mainly of the emission capturing type. This seems to be the case for particulate emissions from various sources, e.g., diesel vehicles or heating units in houses, where filters and other end-of-pipe measures seem to be the main type of available clean technologies. In these cases, our results indicate that appropriate regulation most likely will involve stringent emission standards for diesel cars and heating units in populated city areas and lower standards in rural areas combined with a relatively low tax on fuel to reflect the resulting substantially lower marginal damages of fuel use after filtering.

In addition to obtaining knowledge about marginal damage resulting from emissions at different locations, regulators may also, at least to some extent, be able to ascertain the direction and approximate size of correlations between damage levels and firms' marginal emissions from input, on the one hand, and their sensitivity to input regulation, on the other. To the extent this is possible, the specification of the optimal tax rate on inputs in terms of these correlations (stated in (21)) may prove useful to regulators as a guideline to determine the appropriate level of stringency of the input regulation, e.g., the level of an input tax. In the same way, the specification of optimal regulation intensities for technology standards in (26) may be helpful by indicating how calculations could be operationalized in practice when regulators have information about the relative strengths of the input displacing and emission capturing effects of cleaner technology in the regulated industry.

Generally, one would expect that input displacing technologies play a greater role as the regulator's time horizon increases. In the short run the best one can do may be to add on end-of-pipe filters (capture emissions), while in the long run, where production capital depreciates and is replaced, input substitution possibilities are stronger. Our regulation principle would then suggest that the uniform disincentive for input use (e.g., the tax rate) should increase over time, and that technology regulation should initially generally promote the use of emission capturing technologies, but later shift in the direction of promoting cleaner, input displacing technologies in high damage areas and promoting input using technologies in low damage areas.

6. Conclusion

We have considered a model of location-specific externalities with assumptions and regulatory restrictions that we think reflect important ‘real world’ regulation problems involving many small-scale polluters. For such emission problems regulatory authorities often apply a combination of firm level technology standards and market level restrictions on ‘dirty’ inputs. We have derived general principles for how such regulations should be designed and combined.

Our analysis shows that even if the technology regulation can be finely differentiated, it is efficient to supplement this regulation with undifferentiated, market-level dirty input regulation, and sometimes to apply such regulations with substantial intensity. Furthermore, we find that the optimal design of the input as well as the technology regulation depends critically on whether the cleaner technologies available to firms are mainly dirty input displacing (as, e.g., in the case of the leaching of nutrients and pesticides from farms) or mainly emission capturing (as, e.g., in the case of emission of particulates from households, firms or vehicles where end-of-pipe filtering seems to be the most common available clean technology).

Our results suggest that the uniform dirty input regulation should be applied with a higher intensity (corresponding to a higher tax rate, and one closer to the mean marginal damage of the dirty input in the absence of regulation) when the available clean technologies are mainly input displacing than when they are mainly emission capturing, other things being equal.

We also find that if the clean technologies available to the regulated industry are mainly emission capturing, technology regulation should promote the adoption of cleaner technology in high as well as low damage areas. Regulation intensities should be differentiated so that polluters in high damage areas and polluters for which cleaner technology has a relatively large effect on emissions should be more intensely regulated than firms in low damage areas and firms where cleaner technology has a relatively small effect on emissions.

In contrast, if the clean technologies available to firms are mainly input displacing, technology regulation should promote cleaner technologies in high damage areas, but *discourage* their use in low damage areas. Technology regulation should also be differentiated so that the regulation intensity is relatively large where cleaner technology has a relatively large effect on emissions, and relatively small where cleaner technology has a smaller effect on emissions. The result that technology standards should discourage the adoption of cleaner technologies in low damage areas may, at first, seem counter-intuitive. The reason is that technology regulation should compensate for the larger than optimal incentive to adopt cleaner technologies in low damage areas that the regulation of dirty input generates when the available cleaner technologies are input displacing.

Appendix A. Derivation of (21)

Starting from:

$$z = E\left[iF_g^i \frac{g_z^i}{E\left[g_z^i\right]} \right] \tag{20}$$

and on this applying that 'the mean of the product is equal to the product of the means plus the covariance' gives:

$$z = E\left[i\right]E\left[F_g^i \frac{g_z^i}{E\left[g_z^i\right]} \right] + \operatorname{cov}\left[i, F_g^i \frac{g_z^i}{E\left[g_z^i\right]} \right]$$

$$= E\left[i\right]E\left[F_g^i \frac{g_z^i}{E\left[g_z^i\right]} \right]\left(1 + \frac{\operatorname{cov}\left[i, F_g^i \frac{g_z^i}{E\left[g_z^i\right]} \right]}{E\left[i\right]E\left[F_g^i \frac{g_z^i}{E\left[g_z^i\right]} \right]} \right)$$

Here, the denominator of the fraction in the last parenthesis is the product of two constants that can be moved inside the covariance operator giving:

$$z = E\left[i\right]E\left[F_g^i \frac{g_z^i}{E\left[g_z^i\right]} \right]\left(1 + \operatorname{cov}\left[\frac{i}{E\left[i\right]}, \frac{F_g^i \frac{g_z^i}{E\left[g_z^i\right]}}{E\left[F_g^i \frac{g_z^i}{E\left[g_z^i\right]} \right]} \right] \right)$$

In the fraction furthest to the right, $E[g_z^i]$ cancels giving:

$$z = E\left[i\right]E\left[F_g^i \frac{g_z^i}{E\left[g_z^i\right]} \right]\left(1 + \operatorname{cov}\left[\frac{i}{E\left[i\right]}, \frac{F_g^i g_z^i}{E\left[F_g^i g_z^i\right]} \right] \right) \tag{21}$$

References

Abrella, J. and S. Rausch (2017): ‘Combining price and quantity controls under partitioned environmental regulation’, *Journal of Public Economics* **145**, pp. 226–242.

Ayres, R.U. and A.V. Kneese (1969): ‘Production, Consumption, and Externalities’, *American Economic Review* **59**, pp. 282-297.

Bohm, P. (1981): ‘Deposit-refund Systems: Theory and Applications to Environmental Conservation and Consumer Policy’, Technical Report from *Resources for the Future,* Inc., Washington DC; Johns Hopkins University Press, Baltimore.

Brandt, J., J.D. Silver, L. Frohn, C. Geels, A. Gross, A.B. Hansen, K.M. Hansen, G.B. Hedegaard, C.A. Skjøth, H. Villadsen, A. Zare and J.H. Christensen, (2012): ‘An integrated model study for Europe and North America using the Danish Eulerian Hemispheric Model with focus on intercontinental transport’, *Atmospheric Environment*, **53**, June 2012, pp, 156-176.

Claasen R. and R.D. Horan (2001): ‘Uniform and Non-Uniform Second-Best Input Taxes - The Significance of Market Price Effects on Efficiency and Equity’, *Environmental and Resource Economics* **19**, pp. 1–22.

Christiansen, V. and S. Smith (2015): ‘Emissions Taxes and Abatement Regulation Under Uncertainty’, *Environmental and Resource Economics* **60**, pp. 17–35.

Hansen, L.B. & L.G. Hansen (2014): ‘Can Non-point Phosphorus Emissions from Agriculture be Regulated Efficiently Using Input-Output Taxes?’, *Environmental and Resource Economics* 58 (109).

Holtermann, S. (1976): ‘Alternative Tax Systems to Correct for Externalities, and the Efficiency of Paying Compensation’, *Economica* **43** (169), new series, pp. 1-16.

Højbjerg, A.L. , J. Windolf, C.D. Børgesen, L. Troldberg, H. Tornbjerg, G. Blicher-Mathiesen, B. Kronvang, H. Thodsen, and V. Ernstsen (2015): ’National Kvælstofmodel: Oplandsmodel til Belastning og Virkemidler’, Metoderapport, GEUS.

Klier, T. and J. Linn (2016): ‘The effect of vehicle fuel economy standards on technology adoption’, *Journal of Public Economics* **133**, pp. 41–63.

Kristensen, K., J. Waage-Petersen, C.D. Børgesen, F.P. Vinther, R. Grant and G. Blicher-Mathiesen (2008): ‘Reestimation and further development in the model N-LES, N-LES3 to N-LES4’. *DJF Plant* **139**.

Larson, D., G. Helfand, and B. House (1996): ‘Second-Best Tax Policies to Reduce Nonpoint Source Pollution’, *American Journal of Agricultural Economics* **78** (4), pp. 1108-1117.

Lawrence, H., I. Goulder, W.H. Parry, R.C. Williams III and D. Burtraw (1999):'The cost-effectiveness of alternative instruments for environmental protection in a second-best setting', *Journal of Public Economics* **72**, pp. 329–360.

OECD (2010): 'Taxation, Innovation and the Environment', OECD Publishing, Paris (doi: http://dx.doi.org/10.1787/9789264087637-en).

OECD (2001): 'Environmentally Related Taxes in OECD Countries: Issues and Strategies', OECD Publishing, Paris (http://dx.doi.org/10.1787/9789264193659-en).

Pethig, R. (2006): 'Non-linear Production, Abatement, Pollution and Materials Balance Reconsidered', *Journal of Environmental Economics and Management* **51**, pp. 185-204.

Sengupta, A. (2012): 'Investment in cleaner technology and signaling distortions in a market with green consumers', *Journal of Environmental Economics and Management* **64** (3), pp. 468-480.

Wayne, B.G. and R.J. Shadbegian (2003): 'Plant vintage, technology, and environmental regulation', *Journal of Environmental Economics and Management* 46 (3) , pp. 384-402.