



# Regulation of Location-Specific Externalities from Small-Scale Polluters

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## Abstract

Emission damages caused by small-scale polluters such as farms, vehicles, homes and small businesses are often location-specific and such polluters are often regulated through a combination of location-differentiated cleaner technology standards and uniform, ‘dirty’ input regulation. We investigate how such regulations should be designed and combined under realistic assumptions. We find that if the available cleaner technologies are ‘emission capturing’ (e.g., end-of-pipe filters), they should be encouraged in both high and low damage areas, while if they are ‘input displacing’ (i.e., facilitating replacement of dirty input by cleaner input), they should be encouraged in high damage areas, but discouraged in low damage areas. Dirty input use should always be discouraged and the optimal regulation intensity may be substantial, particularly if the available cleaner technologies are input displacing.

**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 class of regulation problems concerns the regulation of many small-scale polluters where the damage resulting from emissions varies with the polluters' locations.<sup>1</sup> 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. In practice, emissions from small-scale polluters are often regulated indirectly by a combination of technological standards and 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 marginal external cost from emission, the 'damage level', differs across polluters' locations. We assume that the instruments the regulatory authorities can use are technology standards or other technology regulations that can be differentiated across locations and restrictions on dirty input use that cannot be differentiated.<sup>2</sup> Examples of the first type of instruments are emission or engine standards for vehicles and home heating units, technical standards and BAT (best available technology) 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 according to polluters' locations with tougher standards in populated areas 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, nitrogen in fertilizer etc. Such regulations are difficult to differentiate between individual polluters and are typically applied uniformly.

We develop a theoretical model for this type of regulatory situation in order to answer the following research questions: how should these regulatory instruments be combined in order to maximize welfare, and how does the optimal combination depend on the type of cleaner technologies available to the polluters? Cleaner technologies can reduce emissions through two fundamentally different mechanisms. One is 'input displacement', where use of technology helps producers to economize on the use of dirty inputs (as when use of some technological measure makes it possible to replace a dirty input by a cleaner input). The other is 'emission capture', where use of technology gives reduction of emission for given input use (as when an end-of-pipe filter is installed). Generally, cleaner technologies involve both types of effects, but their relative importance can vary substantially. It turns out that optimal regulation depends critically on which type of mechanism that dominates among the available cleaner technologies.

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<sup>1</sup> We are concerned with location-specific rather than plant-specific pollution although the two will often coincide since different plants have different locations. However, one example encompassed by our model are pollution damages from automobiles that differ depending on where the cars are driving, i.e., their locations, although the plants (cars) remain the same.

<sup>2</sup> For a discussion of pollution control measures applied to production inputs versus control measures applied at the recipient level, i.e., ambient-based tax–subsidy schemes, see, e.g., Segerson (1988), Helfand and House (1995) and Shortle et al. (1998). For alternative regulation instruments such as voluntary agreements and refunded emission payments, see, e.g., Goulder et al. (1999), Gersbach and Requate (2004), Sterner and Isakson (2006) and Bonilla et al. (2015).

Our contribution is thus (1) to develop a parsimonious model that encompasses a wide range of pollution problems with many small-scale polluters, where environmental damages vary geographically (from agricultural nutrient emissions to emissions from household heating units), and (2) in this model to derive general principles for optimal regulation and how this depends on whether the available cleaner technologies are predominantly input displacing or emission capturing. We do not know of any prior contributions that have done this.

A number of contributions in the literature have investigated indirect regulation of emissions through input and output taxes, e.g., Ayres and Kneese (1969), Holterman (1976), Bohm (1981), Larsson et al. (1996), Claassen and Horan (2001), Hansen and Hansen (2014), Knittel and Sandler (2018), but these do not consider technology regulation. Other papers have considered various aspects of technology regulation, e.g., Georg et al. (1992), Wayne and Shadbegian (2003), Sengubta (2012), Klier and Linn (2016), but these do not consider input (or emission) regulation in combination with technology regulation. A few papers have considered the interaction of different instruments in the regulation of emissions, e.g., Goulder et al. (1999) and Christiansen and Smith (2015). The paper closest to ours is Christiansen and Smith (2015), who investigate optimal combinations of technology regulation and taxes on emissions (not on input as we consider), but neither this contribution nor the other ones mentioned make the crucial distinction between input displacing and emission capturing technologies that is essential to our results. Finally, in the specific context of regulation of the externalities associated with emissions from automobiles a number of papers study how one can combine regulation of fuel inputs and of automobile characteristics that influence emissions to indirectly regulate the emissions from automobiles. Innes (1996) shows that the optimal tax on a vehicle equals the expected cost of the vehicle's emissions less the expected fuel tax payment. Later papers, Fullerton and West (2002 and 2010) and Bjertnæs (2019) have extended this analysis in a number of ways and found that a vehicle should be subsidized (taxed) if the tax rate on fuel is greater (smaller) than the marginal damage per unit of fuel for the vehicle in question. We find similar results in the simpler and more general model of pollution from small-scale polluters that we consider, but, importantly, in our setting technology regulation may be differentiated geographically between high and low damage areas, which is not the case for the mentioned contributions. Hence, in our setting, technology regulation could be a requirement of catalyzers or a ban on diesel engines for cars driven in specific areas, e.g., in populated inner cities, but not in less populated areas as indeed seen in automobile regulation.

In our model of location-specific externalities, many polluting firms emit at different locations characterized by different damage levels. The profit as well as the emission of each polluter is assumed to depend on the amount of 'dirty' input used and on the intensity by which pollution reducing (input displacing or emission capturing) technologies are used. Authorities can implement uniform disincentives for dirty input use and location-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.

As mentioned, 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 and possibly by substantial intensity, 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 (although with different intensities depending on the polluters' damage levels), 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 a case where authorities are limited to using the two indirect regulation instruments mentioned. 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, e.g., 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 often are those actually used in practice, we believe that providing guidance on how to design and combine them to maximize welfare can provide useful insight for regulators and other interested parties regardless of why regulators chose to limit themselves to these instruments.

In Sect. 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 Sect. 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 Sect. 6 offers some overall conclusions.

## 2 The Regulation Problem Considered: Motivation

In this section, we argue that the *physical* and *regulatory* features of the regulation problem we consider are typical of many important real-world pollution problems. We first specify the *physical* features and give examples of real-world regulation cases where they apply. We then specify the *regulatory* features and argue that they are relevant for the same real-world regulation cases.

We consider production (or consumption) processes characterized by three *physical* features: (1) They use a 'dirty' input that gives rise to damaging emissions, the amount of which can be mitigated by the use of certain 'clean' production technologies. (2) Clean technologies can reduce emissions either by promoting substitution of cleaner input for dirty input, which we call 'input displacement', or by capturing (filtering or in other ways absorbing) emissions that would otherwise occur, which we call 'emission capture', or both. (3) Damages from emissions differ across polluters' locations. These features are characteristic of a number of important water and air pollution problems:

*Water pollution from emissions by agricultural and other small firms.* Fertilizer used in agriculture causes water pollution when nutrients that are not utilized by crops are led to lakes, inlets and coastal waters where they can damage sensitive ecosystems. The damages caused by such emissions vary substantially from field to field because damage depends on how close a field is to sensitive waters, as well as on the soil composition of the field and characteristics of the ground and surface water streams through which lost nutrients are transported to sensitive ecosystems. Farmers are able to reduce fertilizer input, e.g., by

choosing crops that demand less nutrients (so that such crops in our context are *input displacing* technologies). Other examples of input displacing technologies are fertilizer reducing crop rotation patterns and catch crops. Examples of *emission capturing* technologies include wetlands, which can reduce the nutrient content of water flowing through the wetland because of natural denitrification processes. Other small firms like auto repair shops, gas stations, paint and lacquering firms, small-scale industrial producers, pesticide-using farms and fruit producers can cause water pollution by emissions of a broad range of particulates and hazardous chemical compounds; these examples have similar properties with respect to location-dependence and types of cleaner technologies.

*Air pollution from fuel exhausts and other sources.* Fuels burned by heating units in private houses and firms or in vehicle engines cause air pollution when health damaging particulate residuals, NO<sub>x</sub>, CO and SO<sub>2</sub> are emitted to the air. The health damage caused by such emission obviously depends on how close to populated areas the emission takes place. The negative health externality caused by a wood burning stove situated in a residential city area is much greater than from a stove placed in a sparsely populated rural area. Dirty fuel input use can be reduced by using more efficient heating units and vehicle engines or by switching to cleaner fuels with lower content of, e.g., SO<sub>2</sub> and particulates. In our context, these are *input displacing* technologies. Examples of *emission capturing* technologies in this context are smoke filters, catalyzers, etc. In the same way, small firms and farms can cause air pollution by emission of a broad range of non-fuel related particulates and hazardous chemical compounds resulting in location-dependent damages.

The *regulatory* features we consider relate to the information and instruments that we assume the relevant regulatory authorities have access to:

- (1) We assume that the regulator knows the damage level (the marginal external cost of emission) at each polluter's location. This is typically the case, at least approximately, for the pollution problems mentioned above. For example, in Denmark and other countries, authorities use high resolution, air pollution emission-dissemination models of NO<sub>x</sub>, SO<sub>2</sub>, CO and particulates to identify geographical variation in the health effects of emissions.<sup>3</sup> Similarly, for nutrient pollution of waters, emission-dissemination models are used to construct 'retention maps' that identify geographical variation in the environmental damage caused by nutrients lost at the field level.<sup>4</sup>
- (2) We assume that authorities do not regulate emissions directly. This reflects the reality of small-scale polluter regulation in practice where indirect regulation through technology and input restrictions are the predominant instruments (see below). Often, this is because authorities cannot measure or observe damaging emissions directly at reasonable cost. For instance, it would be difficult for authorities to measure the amount of nutrients reaching a lake from a particular farm field or to measure the amount of harmful substances in exhaust reaching a sensitive area from a specific local burner or vehicle engine. Instead:
- (3) Authorities can impose standards or other regulations of the polluters' use of clean technologies. We assume that the regulator can observe the characteristics of each individual polluter's production technology that influences emissions (the type of furnace, smokestack filter or nutrient substituting technology, etc.), and we assume that

<sup>3</sup> See, e.g., Brandt et al. (2012), where valuations of health effects are based on cost-transfer from Danish studies estimating the value of statistical life.

<sup>4</sup> See, e.g., Kristensen et al. (2008) and Højbjerg et al. (2015).

- the authorities can 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 the use of technologies as well as the polluters’ damage levels are observable, we assume that *technology incentives can be differentiated across polluters’ locations according to damage levels* (see real-world examples below).
- (4) Finally we assume that *authorities can regulate the use of dirty input, but input regulation cannot be differentiated across polluters*. For instance, a uniform tax on input can be imposed, but one that is differentiated across polluters’ locations cannot, as would be the case for a common tax collected at the distributor level (see further motivation below).

These features reflect how small-scale polluters are typically regulated in practice. Polluting farms, firms, households and vehicles are often 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.<sup>5</sup> Similarly, regulation of industrial production technologies is widely applied in the USA.<sup>6</sup> 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.<sup>7</sup> Vehicles in the EU and the USA are subject to emission standards that demand the use of catalytic converters and filters that reduce particulates, CO and NO<sub>x</sub> emissions in exhaust fumes.<sup>8</sup>

In many cases, because installation of the required technology can be verified by inspection, controlling compliance is feasible even when regulation is differentiated across polluters. 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 often are, differentiated geographically 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, regulation often stipulates tougher emission standards for vehicles driving in inner cities than elsewhere like with a ban on diesel cars, 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.

In contrast to technology regulation, input regulation is typically not differentiated across polluters. One reason is the risk of ‘illicit trade’ in inputs. 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 differentiated according to the damage level at each individual polluter’s location) would likely create differences in the pre-tax marginal profit of input across

<sup>5</sup> See, e.g., the EU Industrial Emissions Directive, which can be found at: <http://ec.europa.eu/environment/industry/stationary/index.htm>.

<sup>6</sup> 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>.

<sup>7</sup> See, e.g., the EU Water Framework Directive: [http://ec.europa.eu/environment/water/water-framework/index\\_en.html](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>.

<sup>8</sup> See, e.g., <http://eurlex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2007:171:0001:0016:EN:PDF>.

polluters, thereby making such transactions profitable, which would undermine the intended differentiation.<sup>9</sup> Another reason could be that differentiated input taxes are considered unfair. However, undifferentiated (uniform) taxes and regulations of ‘dirty’ inputs are applied in many cases involving small-scale polluters.<sup>10</sup> Vehicle and heating fuels are uniformly taxed and their specifications and additives are uniformly regulated in many US and European states, while taxes, quotas and other uniform regulations are imposed on farm inputs such as fertilizer and pesticides in many European countries.<sup>11</sup>

The purpose of this paper is to establish principles for (second) best possible regulation given the 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* (location and damage level dependent) regulation of clean technologies. We proceed by setting up our model formally.

### 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. For simplicity we assume that this damage level is 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 levels, 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  $E(i) \equiv \int_0^1 iq(i)di$ .<sup>12</sup>

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 one 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  $i$ .

<sup>9</sup> 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 drives is evaded if the owner buys fuel in a low tax area and drive 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’.

<sup>10</sup> See, e.g., OECD (2001) and (2010).

<sup>11</sup> 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.

<sup>12</sup> 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.

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  $\Pi$ . 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 technology: an increase in the quality index  $h_i$  for given  $g_i$  may well reduce profit.<sup>13</sup>

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<sup>14</sup>:

$$W^i(g_i, h_i) \equiv \Pi^i(g_i, h_i) - F^i(g_i, h_i)i \tag{1}$$

while the welfare contribution of the whole industry is:

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

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 zero), 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, 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  $h_i$ :

$$F^i_h(g_i, h_i) \leq 0 \tag{3}$$

$$\Pi^i_{gh}(g_i, h_i) \leq 0 \tag{4}$$

<sup>13</sup> 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 typically not be an appropriate assumption.

<sup>14</sup> Associating economic surplus with profit is essentially a ‘small industry’ assumption: the full value added is profit plus wage income, but we assume implicitly that workers can obtain the same income for the same effort in other sectors (the income possibilities in these are not affected by the industry considered). Note however, that although the sector considered is small in a value added sense, it may well account for a large proportion of pollution. In many western countries, e.g., agriculture stands for a relatively small part of GDP and employment, but for a large part of water pollution with nutrients.



Condition (4) implies that if a firm is induced to use a cleaner technology, it will not be profitable for it to use more of the dirty input, but generally less. We consider assumptions (3) and (4) as natural requirements for a ranking of technologies representing cleanness.<sup>15</sup>

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 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.:

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

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.:

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

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.<sup>16</sup>

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. An example of this is an end of pipe technology where operating costs depend on the amount of the dirty input used, e.g., filters based on

<sup>15</sup> Since  $h_i$  is not an amount of input that can be substituted for 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.

<sup>16</sup> 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.

costly chemical reduction techniques where filter replacement and maintenance costs depend on the amount of pollutant filtered.<sup>17</sup>

In line with the discussion in Sect. 2, we make the following assumptions regarding the informational and regulatory possibilities of authorities. They are able to 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,  $(h_i, g_i)_{i \in [0,1]}$ . Among our realistic features is that redistribution of dirty input between firms (if advantageous) cannot be prevented. This implies a restriction on which plans could possibly be achieved: the marginal be the same for all firms. We thus define a 'feasible plan' as one for which:

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

A 'second best' plan is defined as a plan that maximizes  $W$  defined in (2) over all feasible plans, i.e., plans that satisfy (7).

In the following we first characterize the (unique) second best plan without appealing to specific regulatory measures and then show how this plan can be implemented by an appropriate combination of uniform dirty input regulation and targeted regulation of clean technologies. Proceeding this way we not only derive the best possible regulation given the instruments available, but also show that this regulation gives the best outcome that can be obtained given that redistribution of dirty input among polluters cannot be prevented.

Our characterization of a second best plan 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.,  $g_i = g^i(h_i, z)$ , where  $\Pi_g^i(g^i(h_i, z), h_i) = z$ . The sensitiveness of input use with respect to the clean technology index  $h_i$  and with respect to the required marginal profitability  $z$  according to this function will be of importance in the following. By implicit differentiation:

<sup>17</sup> 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.

<sup>18</sup> Note that it is without limitation 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.

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

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

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

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

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:

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

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

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

This is a marginal condition stating that for each firm  $i$ , the marginal profitability 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,  $(F_g^i g_h^i + F_h^i)i$ .

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  $W^i(g^i(h_i, z), h_i)$  gives the social welfare contribution of firm  $i$  (at the socially optimal technology given  $z$ ) as a function of  $z$  and  $i$ :

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

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

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

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:

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

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

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

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  $z$ :

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

which can be rewritten as:

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

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

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

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 suitable for interpretation (as explained in the next section). Letting the ‘random variables’ be  $i$  and  $F_g^i g_z^i / E[g_z^i]$ , (20) can be rewritten as<sup>19</sup>:

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

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),  $F_g^i = F_g^i(g^i(h^i(z, i), z), h^i(z, i))$  and  $g_z^i = g_z^i(h^i(z, i), z)$ , so both sides of each equation are functions of  $z$  alone. We assume that (20) or (21) determines the optimal  $z^*$  uniquely. Since the right-hand side of (20) or (21) only involves strictly positive components, generally  $z^* > 0$ . Overall, we have shown that given our assumptions the characterization of a second best plan is:

<sup>19</sup> See Appendix A for the details.

**Proposition 1** *Let  $z^* > 0$  be the unique  $z$  determined by (20) (or (21)). A second best plan is a tuple  $(h_i^*, g_i^*)_{i \in [0,1]}$ , which, for this  $z^*$ , fulfils (7) as well as the marginal condition (12), that is:*

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

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

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 cleanliness. 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:

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

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

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

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

the conditions (24) and (25) become equivalent to (22) and (23). This proves that given our assumptions we have:

**Proposition 2** *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, it is necessary to apply both of the instruments considered here to implement the second best plan.

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.

### 5.1 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),  $\Pi_g^i(g_i, h_i) = F_g^i(g_i, h_i)i$  and  $\Pi_h^i(g_i, h_i) = F_h^i(g_i, h_i)i$ . Assume that these determine the first best plan,  $(h_i^o, g_i^o)_{i \in [0,1]}$ , uniquely. With firm differentiated taxes on both input and technology cleanliness 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  $\Pi_g^i(g_i, h_i) = t_i$  and  $\Pi_h^i(g_i, h_i) = s_i$ . Hence, setting the tax rates  $t_i = F_g^i(g_i^o, h_i^o)i > 0$  and  $s_i = F_h^i(g_i^o, h_i^o)i \leq 0$  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,  $F_h^i(g_i^o, h_i^o) = 0$ , 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. Our rule for the optimal tax rate derived from Eq. (20),  $t = E[i \cdot F_g^i \cdot g_z^i / E[g_z^i]]$ , confirms this intuition and tells exactly *which* mean is appropriate: for each firm the marginal damage caused by use of the dirty input,  $i \cdot F_g^i$ , is multiplied by the relative ‘tax sensitiveness’ at the location,  $g_z^i / E[g_z^i]$ , and the products are then weighted by the relative number of firms at each location,  $q(i)$ .<sup>20</sup> This generates 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 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

<sup>20</sup> A similar rule was derived in Diamond (1973) for a consumption good externality, and later applied in an empirical study of the effect of gasoline taxes on congestion and other externalities of personal transportation in Knittel and Sandler (2018).

(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),  $1 + \text{cov}[i/E[i], F_g^i g_z^i / E[F_g^i g_z^i]]$ . 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 Eq. (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),  $[F_g^i(g_i^*, h_i^*)i - z^*]g_h^i(h_i^*, z^*)$ , is (the negative of) the marginal social benefit of a marginal increase in the technology index arising from the input displacing effect of the cleaner technology alone. Here  $g_h^i(h_i^*, z^*)$  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,  $z^*$ .<sup>21</sup> 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’ 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 technology regulation should therefore reinforce the effect. 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.

<sup>21</sup> 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.

## 5.2 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 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,  $g_z^i(h_i, z) = k_i$ .<sup>22</sup>

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 (mean 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  $z^* < z^u$ .

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.<sup>23</sup>

<sup>22</sup> 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  $\Pi_{gh}^i(g_i, h_i) = 0$ . 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  $z$ .

<sup>23</sup> 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. Hence, the optimal tax rate would 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.



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:

$$s_i = F_h^i(g_i^*, h_i^*)i < 0 \quad (27)$$

Here the appropriate tax rate is negative for all firms, so optimal technology regulation always induces or mandates the adoption of technologies that are cleaner than the firms would otherwise have found profitable. Furthermore, 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, technology regulation should induce all firms to use cleaner technologies.

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:

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

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 firms would otherwise have found profitable in areas where the marginal damage resulting from the dirty input use,  $F_g^i(g_i^*, h_i^*)i$ , 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 otherwise have 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 otherwise have found profitable in these areas.

### 5.3 Practical Applicability of the Regulation Principle

The analysis of this paper is theoretical and general. It would, of course, be of interest to 'bring it to the data' in order to derive specific appropriate regulation in practice. This would require a focus on particular sectors, e.g., agriculture and water pollution from nutrients or the automobile sector and air pollution from particulates etc., in order to obtain the required knowledge of, e.g., the firms' profit and emission functions. While this is an obvious subject for future research, we think that even at the present level our analysis and the regulation principles following from it may be of use for outlining some overall guidelines for regulation in practice.

Regulators may often be able to identify the relative importance of input displacing effects versus 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 and planting catch and winter crops. All of these technologies are 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 marginal nitrogen emissions resulting from fertilizer use can be expected to be relatively large even in the regulated state, 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 induced by input taxation. However, 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 may mainly be 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 relatively stringent emission standards for diesel cars and heating units in populated city areas and less stringent standards in rural areas. This should be combined with a relatively low tax on fuel to reflect the resulting substantially lower marginal damages of fuel use in the regulated state when filtering technologies are mandated through cleaner technology standards.

In addition to obtaining knowledge about marginal damage resulting from emissions at different locations, regulators may also be able to acquire knowledge of 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. If 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 regulation stringency should depend on 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. For automobiles and air pollution from fuel exhaust, for instance, it may be that catalyzers are the most relevant technology in the short run (for a given fleet of cars), while in the long run shift to electric and other low emission cars is the most relevant technology. 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 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 optimal uniform regulation of dirty input generates when the available cleaner technologies are input displacing.

In the longer run, the relevant clean technologies are probably to a large extent input displacing, which thus points to regulation that relatively intensely discourages the use of dirty input, encourages cleaner technologies in high damage areas and discourages them in low damage areas. The latter feature, though efficient, could perhaps be hard to 'sell' politically. Even so, our regulation principle may provide regulators with important guidance when deciding about best possible regulation given the political limitations. Furthermore, the feature need not be politically impracticable. For instance, in the agricultural, water pollution example alluded to several times above some crops are less fertilizer demanding than others are. A relevant policy obeying our regulation principle could be one that taxes the nitrogen content in

fertilizer and animal feed considerably, subsidizes the less fertilizer demanding crops in high damage areas and subsidizes the more fertilizer demanding crops in low damage areas. Such a policy would treat farmers symmetrically in that all farmers pay an input tax and can receive some form of crop subsidies. In contrast to policies where farmers in high damage areas are subject to tougher regulation, it would impose similar costs on farmers in high and low damage areas and for this reason, it might be considered politically acceptable.

Our analysis is theoretical and only allows for one kind of emission. Analyses of how to regulate firms with more than one kind of emission and studies that quantify optimal regulation and compares it to current actual regulation for specific, real-world cases would seem to be useful future research.

## Appendix A. Derivation of (21)

Starting from:

$$z = E \left[ i F_g^i \frac{g_z^i}{E[g_z^i]} \right] \quad (29)$$

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

$$\begin{aligned} z &= E[i]E \left[ F_g^i \frac{g_z^i}{E[g_z^i]} \right] + \text{cov} \left[ i, F_g^i \frac{g_z^i}{E[g_z^i]} \right] \\ &= E[i]E \left[ F_g^i \frac{g_z^i}{E[g_z^i]} \right] \left( 1 + \frac{\text{cov} \left[ i, F_g^i \frac{g_z^i}{E[g_z^i]} \right]}{E[i]E \left[ F_g^i \frac{g_z^i}{E[g_z^i]} \right]} \right) \end{aligned}$$

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:

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

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

$$z = E[i]E \left[ F_g^i \frac{g_z^i}{E[g_z^i]} \right] \left( 1 + \text{cov} \left[ \frac{i}{E[i]}, \frac{F_g^i g_z^i}{E \left[ F_g^i g_z^i \right]} \right] \right) \quad (30)$$

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