

# The Economics of Abatement Based on Explicit Technologies for Output Reduction and Control

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## Abstract

The contribution of this paper lies in deriving socially optimal abatement (pollution avoidance) explicitly from separate technologies for production as well as control, where ‘control’ refers to decomposition of pollutants into harmless matter. This would help to construct welfare maximizing interventions such as Pigouvian taxes, given that a firm would respond to such an intervention by undertaking ‘reduction’ of its output and ‘control’, the two constituents of socially optimal abatement. Two cases are considered in this paper: zero and positive marginal cost of control at zero level of control. Cost minimization of a targeted level of abatement implies that the first case results in positive levels of both ‘reduction’ and ‘control’. The second case is associated with reduction equaling abatement for abatement below or equal to a threshold level, and positive levels of ‘reduction’ and ‘control’ otherwise. Thus, low enough marginal damages would be associated with low socially optimal abatement facilitated only through reduction; otherwise, a high enough socially optimal abatement facilitated by ‘reduction’ as well as ‘control’ would result. Further, an increase in the efficiency of the control technology which lowers the mentioned threshold level might have no impact on the magnitude of socially optimal level of abatement when marginal damages are low enough.

**Keywords:** reduction, control, abatement, marginal cost

## 1. Introduction

Profit maximizing firms undertake abatement only when they are induced to do so by measures such as taxation or command-and-control legislation. In the absence of these interventions, a profit maximizing firm will determine the cost minimizing input combination for every level of output, and then choose to produce the level of output that maximizes profits, given the minimized cost for producing different levels of output.

Abatement is undertaken when a social planner makes the firm pay in some way for the damage caused to the environment by emissions, thereby inducing it to reduce its emissions. In the literature there have been several ways of looking at the problem of optimal abatement. One way is to think of a cost of production which depends on a) output and b) actual emissions generated through production and abatement -- with the partial derivatives of cost with respect to the two variables being positive and negative respectively (Helfand et al., 2000) -- or equivalently on a) output and b) abatement, the difference between gross emissions determined by the level of output and actual (net) emissions. The underlying assumption is that abatement of emission for a given level of output involves expenditure. Given such a cost function, the social planner chooses output and emission levels to maximize social welfare given by firm profit less damages from emissions. Note that while reducing emissions for a given level of output drives down profits and therefore will be avoided by an unrestrained profit maximizing firm, the social planner’s concern for damages from emissions will result in a depressing impact on output and/or emissions through suitable restraints.

Stern and Corria (2000) attempt a modified version of the second case, considering net emissions to be a function of pollution control, say through filters, and output. But the sensitivity of net emissions to control and output remains a black box and there is no attempt to determine the relationship between this sensitivity and the separate technologies determining (i) output or its reduction and (ii) control or reduction of net emission, given a constant level of gross emissions. This paper dissects this black box by considering separate technologies and

then uses the standard technique of maximizing welfare defined as total benefit to the firm from output less damage, a function of net emissions. The planner thus tries to influence net emissions by suitably inducing a 'reduction of output' and 'control', the use of methods of filtration of gross emissions. In this regard, it is assumed to use its explicit knowledge of the technologies regarding production and control. Thus, the influence exerted by social planner on net emissions is influenced by the nature of these technologies.

Note that there are other old approaches which only consider one instrument at a time for solving the problem of welfare maximization. For example, Downing and White (1986) considers the welfare maximization problem as being equivalent to equating the increasing marginal cost of controlling emissions to the tax rate on emissions set appropriately by the social planner. *Ceteris paribus*, any improvement in the technology for control of emissions will lead to an increase in the control of emissions. There is no explicit role here of the technology of production of the commodity.

Yet another older approach of optimizing abatement/emission is by equating the marginal damage from emission enhancing output to the net private marginal benefit from production (Gunawardena, 2010; and Pearce & Turner, 1990), defined as marginal revenue less marginal cost of production. The problem here is that there is an implicit assumption that abatement can only occur if output is reduced; in real life, the firm might go in for abatement which is an optimal combination of output reduction and emission control.

In short, the literature is marked by the absence of a general theoretical model which arrives at an abatement cost that explicitly incorporates the separate technologies associated with the two ways of reducing emissions (abatement): (a) reducing output (reduction) and (b) given output, filtering out the emissions or decomposing them into harmless parts using equipment such as electrostatic precipitators (control). A given amount of abatement can therefore be achieved by using various alternative combinations of reliance on these two mechanisms. Ideally the social planner should choose or induce a choice of a social welfare maximizing combination through instruments such as taxes. The objective of this paper is to propose a theoretical framework that shows how abatement outcomes will be affected by exogenous factors, such as the technology of controlling emissions or the cost of production.

An advantage of the proposed theoretical model is that we exactly specify abatement and define it as the reduction in emissions from the benchmark level of emissions associated with private optimization of profits when no penalty for emissions is imposed. This allows us to compare abatement across various technological scenarios.

Note that in this paper we consider abatement to be associated with a cost on firms. Recent work has considered abatement to be associated with benefits in regard to worker productivity; other work points out situations in which pollution regulation can be used by oligopolistic firms to collude, restrict output and reap profits (Pang, 2018; and Anand & Giraud-Carrier, 2020). Such benefits from abatement and pollution regulation fall outside the scope of the framework developed in this paper.

The layout of this paper is as follows. In the next section we lay out the framework in which abatement is possible through control as well as reduction and highlight some important results based on broad assumptions. Section 3 concludes.

## **2. Socially Optimal Abatement with Two Means of Abatement**

We now look at the case where emissions can be curbed through a combination of reduction from the private optimum and control. Reduction is considered with respect to the private optimum as this is the output that the profit maximizing firm produces in the absence of government intervention. Note that given our assumption of an increase in output by one unit translating into an additional unit of emissions when nothing is done to control the emissions from that additional production, the magnitude of reduction is equal to that of the abatement (decrease in emissions) it results in. Control on the other hand is reduction of emissions which does not rely on any reduction in output; once production of a certain level of output results in an equal number of units of emissions, control, the filtration of emissions or the decomposition of some part of it into harmless matter, can be used to further reduce the level of emissions that humans are subjected to. Thus, any achieved level of total abatement is the sum of reduction and control and the objective of the social planner would be to choose a level of total abatement as well as the combination of reduction and control that would result in that abatement so that social welfare is maximized.

To explain this further we can use alternative terminology. The production of output, given our assumptions, automatically results in an equal number of units of emissions. This number captures the gross emissions. When gross emissions are subjected to abatement through control the result is net emissions. Net emissions are less

than gross emissions in case of positive control and equal to gross emissions in the case of zero control. Thus, we have the following identities.

$$\text{Output} = \text{Gross Emissions} \quad (1)$$

$$\text{Reduction} = \text{Privately Optimal Gross Emissions} - \text{Actual Gross Emissions} = \text{Privately Optimal Output} - \text{Actual Output} \quad (2)$$

$$\text{Control} = \text{Actual Gross Emissions} - \text{Actual Net Emissions} \quad (3)$$

$$\begin{aligned} \text{Total Abatement} &= \text{Reduction} + \text{Control} = \\ &(\text{Privately Optimal Output} - \text{Actual Output}) + (\text{Actual Gross Emissions} - \text{Actual Net Emissions}) \end{aligned} \quad (4)$$

Thus, the objective of the planner would be to choose the welfare maximizing (a) abatement and (b) its allocation between reduction and control. Because of (4) this is equivalent to maximizing welfare by choosing any two of the following three: (a) total abatement; (b) control; and (c) reduction. Again, paying attention to (4), if we assume production technology and price of output to be given, thereby implying a given privately optimal amount of output and gross emissions, then objective of the planner can be equivalently stated as maximizing welfare with respect to actual output (actual gross emissions) and control.

Mathematically, the social planner's problem is as follows:

$$\max_{A,R} \text{NTB}(y - R) - \text{CC}(A - R) - \text{TD}(y - A)$$

where  $y$  denotes the privately optimal output,  $R$  denotes reduction and  $A$  denotes total abatement. Therefore,  $y - R$  will be the actual amount of output produced and  $A - R$  would equal the amount of control. Note also that  $y - A$  would equal the total amount of net emissions. The notation  $\text{NTB}$ ,  $\text{CC}$  and  $\text{TD}$  denote net total benefit (revenue less production cost), control cost and total damage respectively and are functions of  $y - R$ ,  $A - R$  and  $y - A$  respectively. The first of these is increasing and concave in  $y - R$  given that its derivative is net marginal benefit or price less increasing marginal cost of production, the second increasing and convex in the level of control,  $A - R$  and the last also increasing and convex in  $y - A$ , the level of net emissions. As a result, the first order conditions for an interior solution (positive  $A$  as well as  $R$ ), if it exists, are given by

$$\text{NMB}(y - R) = \text{MCC}(A - R) \quad (5)$$

$$\text{MCC}(A - R) = \text{MD}(y - A) \quad (6)$$

where  $\text{NMB}$ ,  $\text{MCC}$  and  $\text{MD}$  denote net marginal benefits, marginal control costs and marginal damage respectively. From (5) and (6) we have

$$\text{NMB}(y - R) = \text{MCC}(A - R) = \text{MD}(y - A) \quad (7)$$

This allows us to solve the problem in two steps:

First,  $\text{NMB}(y - R) = \text{MCC}(A - R)$  for a given level of  $A$  yields cost minimizing reduction as a function of targeted abatement and *y* i.e.,  $R(A, y)$ .  $A - R(A, y)$  yields the control which minimizes cost for generating abatement equal to  $A$ . Inserting  $R(A, y)$  in  $\text{MCC}(A - R)$  and equating that to  $\text{MD}(y - A)$  would yield values of  $R$  and  $A$  that solve (7),  $R^*$ ,  $A^*$ , which are the welfare maximizing levels of  $R$  and  $A$ .

Consider  $\text{MCC}(0) = 0$  i.e., marginal cost of control at zero control is 0. Note that for positive abatement,  $\text{NMB}(y - A) > \text{NMB}(y) = \text{MCC}(0) = 0$ . Similarly,  $\text{MCC}(A) > \text{NMB}(y) = 0$ . Thus, any corner solution can be improved upon, in terms of expenditure reduction, by reallocation of abatement to facilitate an interior solution. Thus, the cost minimizing allocation of targeted abatement between reduction and control has to be an interior solution. This involves equating  $\text{MCC}(A - R)$  to  $\text{NMB}(y - R)$  (equation (5)) to yield  $R(A)$  and this equated  $\text{MCC}/\text{NMB}$  is the marginal abatement cost,  $\text{MAC}(A)$ .

Enhancement of the target for abatement in the case,  $\text{MCC}(0) = 0$  implies an increase in the welfare maximizing levels of both reduction and control. This is because the equality  $\text{NMB}(y - R) = \text{MCC}(A - R)$  would be disturbed if only one out of reduction and control were to increase. Thus  $\text{MAC}(A)$  is upward sloping. Further since any increase in abatement is to be distributed between both reduction and control the slope of the  $\text{MAC}(A)$  curve will be less than the slopes of the  $\text{NMB}$  and  $\text{MCC}$  curves.

Consider  $\text{MCC}(0) > 0$ . Throughout this paper when we refer to an increase/decline in  $\text{MCC}(0) > 0$ , we mean a vertical shift in the  $\text{MCC}$  curve given by this increase/decline. We define  $\bar{A} > 0$ , but not exceeding  $y$ , as the threshold level of abatement such that  $\text{MCC}(0) = \text{NMB}(y - \bar{A})$  which has the property that  $\text{NMB}(y - A) \leq \text{MCC}(0)$  for  $A < \bar{A}$ . This threshold has the following property: for  $A \leq \bar{A}$ ,  $\text{MAC}(A)$ , the marginal cost of abatement, would be given by  $\text{NMB}(y - A)$  and for  $A > \bar{A}$ , targeted abatement would be allocated between

positive levels of reduction and control with  $MAC(A) < \min[MCC(A), NMB(y - A)]$  and given by  $NMB(y - R) = MCC(A - R)$ , with  $R$  chosen so as to result in this equality. The  $MAC(A)$  curve is upward sloping as it coincides with the  $NMB(y - A)$  curve to begin with and then given by the mentioned equality.

Given that for  $A > \bar{A}$ , any increase in abatement is to be distributed between reduction and control the slope of the  $MAC(A)$  curve will be less than the slopes of the  $NMB$  and  $MCC$  curves.

Note that  $\bar{A}$  is increasing in the magnitude of  $MCC(0)$  for  $NMB(0) > MCC(0)$ . For  $MCC(0) > NMB(0)$ ,  $\bar{A} = y$ . This implies that  $y$  would continue to serve as the threshold level of abatement for such high magnitudes of  $MCC(0)$ . Thus, all possible levels of abatement would be carried out only through reduction and there would be no difference between the  $MAC(A)$  and  $NMB(y - A)$  curve.

Our results so far can be summed up through Proposition 1:

**Proposition 1:** (a) When  $MCC(0) = 0$  the cost minimizing combination of control and reduction for achieving any targeted abatement emerges from equating  $MCC(A - R)$  to  $NMB(y - R)$  and involves a positive amount of reduction as well as control which are both increasing in the target. As the targeted abatement increases, the marginal cost of abatement,  $MAC(A)$ , defined as the equated  $MCC/NMB$ , increases and displays a slope which is less than the slopes of the  $MCC$  and  $NMB$  curves.

(b) When  $MCC(0) > 0$ ,  $MAC(A)$  coincides with  $NMB(y - A)$  for  $A \leq \bar{A}$  where  $\bar{A}$  is the level of abatement such that (i) it solves  $MCC(0) = NMB(y - A)$  at a value less than  $y$  or (ii) it equals  $y$  for  $MCC(0) \geq NMB(0)$ .  $MAC(A)$  is given by the level of equated  $MCC/NMB$  for  $A > \bar{A}$ , if such abatement is possible, with abatement achieved through positive levels of both reduction and control which keep on increasing with targeted abatement. As is true for case (a), the marginal cost of abatement increases with abatement but its slope with respect to abatement is less than the slopes of  $MCC$  and  $NMB$  curves.

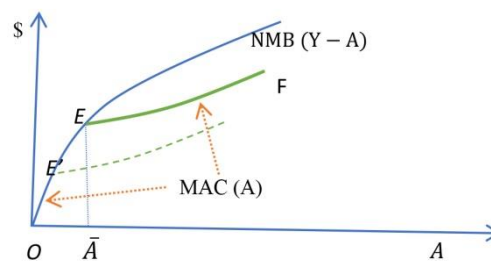


Figure 1. The Marginal Cost of Abatement Curve for  $MCC(0) > 0$

Figure 1 illustrates case (b) in Proposition 1. The steep curve depicts  $NMB(Y - A)$  whereas  $MAC(A)$  is given by curve  $OEF$ , coinciding with  $NMB(Y - A)$  up to an abatement level of  $\bar{A}$  and then becoming flatter and falling below  $NMB(Y - A)$  for levels of abatement which are associated with both reduction and control. Note that as  $MCC(A - R)$  shifts downwards with a decline in  $MCC(0)$ , the threshold level of abatement,  $\bar{A}$ , would become smaller and therefore the steep section of the  $MAC(A)$  curve would become shorter and end at  $E'$  with the rest of  $MAC(A)$  taking the path given by the dashed curve.

If the planner is targeting a level of abatement denoted by  $A^*$  then she should levy a per unit tax,  $T^*$  on emissions such that  $MAC(A^*) = T^*$ . If she chooses (i) tax  $\hat{T}$  on emissions such that  $MCC(A^*) = \hat{T}$  or (ii) tax  $\ddot{T}$  such that  $NMB(y - A^*) = \ddot{T}$ , as suggested by earlier studies (see introduction), then in the case of  $MCC(0) = 0$  both  $\hat{T}, \ddot{T} > T^*$  given that the  $MAC(A)$  curve lies below the  $NMB(y - A)$  as well as  $MCC(A)$  curves. In the case of  $MCC(0) > 0$ , given that the  $MAC(A)$  curve coincides with the  $NMB(y - A)$  curve for  $A \leq \bar{A}$  and then lies below it, and the  $MAC(A)$  curve lies below the  $MCC(A)$  curve throughout, we have  $\hat{T} = T^*$  for  $A^* \leq \bar{A}$  and  $\ddot{T} > T^*$  otherwise; and  $\hat{T} > T^*$  for any  $A^*$ . For the profit maximizing firm which knows about control technologies its actual abating behavior will be given by  $MAC(A) = T$  where  $T$  is any per unit tax on emissions. Therefore, given the above conclusions, the choice of  $\hat{T}$  or  $\ddot{T}$  by the planner as per unit tax on emissions will result in abatement greater than  $A^*$  in the case of  $MCC(0) = 0$ ; and for  $MCC(0) > 0$ , abatement equal to  $A^*$  for  $A^* \leq \bar{A}$  and greater than  $A^*$  for  $A^* > \bar{A}$  when tax chosen is  $\ddot{T}$ , and abatement greater than  $A^*$  always when tax chosen is  $\hat{T}$ .

Once the planner knows the welfare maximizing level of abatement, she can attain this level of abatement by choosing a tax  $T$  on per unit emissions which is equal to the  $MAC$  at this level of abatement. A discussion on the determination of the welfare maximizing level of abatement and its sensitivity to the technologies for production

and control follows as per equation (7).

Assume  $MCC(0) = 0$  which implies  $MAC(A) = 0$  for  $A = 0$  – the equated NMB ( $y - R$ ) and  $MCC(A - R)$  or  $MAC(A)$  approaches zero as  $A$  tends towards 0. Also assume zero marginal damage at zero net emissions, i.e.  $MD(y - A) = 0$  for  $A = y$ . Figure 2 below shows that the socially optimal level of abatement,  $A^*$  is given by the intersection of  $MAC(A)$  and  $MD(y - A)$ , the first an upward sloping curve from the origin and the second a downward sloping curve in abatement-dollar space, attaining zero height at  $A = y$ . Thus,  $A^* < y$  i.e., it is never socially optimal to have zero net emissions, given the assumptions made. Finally,  $MCC(0) = 0$  implies, given Proposition 1, that  $A^*$  will be achieved through positive reduction and positive control.

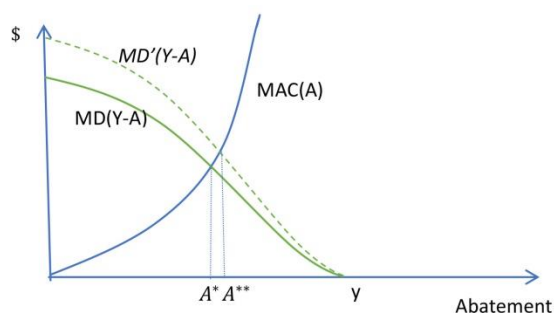


Figure 2: Change in Welfare Maximizing Abatement for a Rightward Shift in the Marginal Damage Curve, Given  $MCC(0) = 0$  and Zero Marginal Damage at Zero Net Emissions

Continuing with the same assumptions, it is easy to see that an upward movement of the MD curve as a result of an upward revision of estimates of MD, with the new MD curve now given by a dashed curve, will enhance the welfare maximizing level of abatement, now given by  $A^{**}$ . Since  $MAC(A)$  is  $MCC/NMB$  emerging from the equality  $MCC(A - R) = NMB(y - R)$ , Proposition 1 tells us that, control and reduction, both initially positive, will both increase as a result of the increase in abatement that follows the mentioned upward revision of MD.

Referring to the subject matter of Figure 2 again, a downward movement in the  $MCC(\cdot)$  curve (not in Figure 2) will lead to the same in the  $MAC(A)$  curve and result in a higher level of socially optimal abatement as well as a lower level of  $MAC(A)$  at equilibrium, the per unit tax on emissions that brings about that abatement. A lower  $MAC(A)$  at equilibrium implies lower  $NMB(y - R)$  in equilibrium and hence a lower reduction in equilibrium, given that  $MAC(A)$ , by definition, is the equalized NMB and  $MCC$  and we have assumed no change in production technology. Hence, we can conclude that an improvement in the control technology, which leads to a downward movement in the  $MAC(A)$  curve, will lead to an increase in abatement, a fall in reduction, and an increase in control which exceeds the increase in abatement. In other words, the difference between the privately optimal level of output and the socially optimal level will keep on shrinking with improvements in control technology while the amount of net emission will decline.

On the other hand, consider a lowering of marginal cost of production. We add some uniformity conditions:  $MC(x) = a + bx$  where  $a, b > 0$  and  $x$  is output. A lowering of marginal cost of production is possible in two ways: through a reduction in  $a$  or in  $b$ . We only discuss the case of reduction in  $a$  in order to save space. Note

that  $NMB(y - R) = bR$  and  $y = \frac{P-a}{b}$  where  $P$  is price given exogenously. A reduction in  $a$  increases  $y$  but

produces no change in the  $NMB(y - R)$  curve as a function of  $R$ . Thus, given unchanged  $MCC(\cdot)$ , the  $MAC(A)$  curve remains unchanged. However, the mentioned increase in privately optimal output (from  $y$  to  $y^1$  in Figure 3) implies that the MD curve (see Figure 3) shifts up or equivalently by a horizontal distance of  $y^1 - y$  to the right. This in turn implies an increase in socially optimal abatement from  $A^*$  to  $A^{**}$  with MD in equilibrium rising. Thus, the increase in abatement would be less than  $y^1 - y$ . In other words, the socially optimal net emissions would increase.

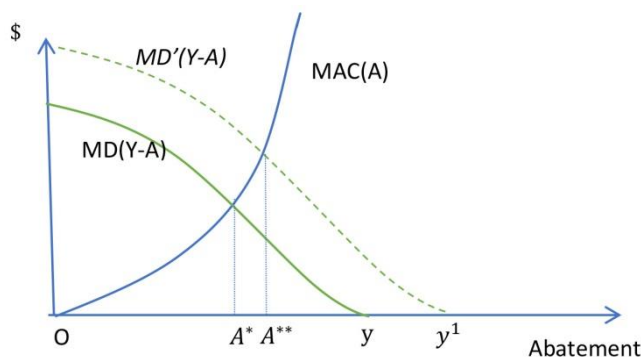


Figure 3: Change in Welfare Maximizing Abatement for a Decline in Vertical Intercept of the Linear Marginal Cost of Production Curve When  $MCC(0) = 0$

**Proposition 2:** Consider the case of  $MCC(0) = 0$ , and  $MD(y - A) = 0$  for  $A = y$  i.e., zero marginal damage at zero net emissions. The socially optimal level of abatement in this case exhibits the following properties:

- (i) It increases after an upward movement of the MD curve but this increase is facilitated by an increase in both reduction and control.
- (ii) It increases following a downward movement of the  $MCC(A-R)$  curve in control-dollar space and the consequent downward shift of the  $MAC(A)$  curve, and this increase is facilitated by an increase in control and a decrease in reduction (an increase in the socially optimal level of output)
- (iii) If we assume marginal cost of production as an affine function of output, socially optimal abatement increases following a vertical downward shift in the marginal cost curve but net emissions increase.

It is easy to see what would happen if we combine the two assumptions of  $MCC(0) = 0$ , and  $MD(y - A) > 0$  for  $A = y$ .

**Proposition 3:** Assume  $MCC(0) = 0$  and  $MD(y - A) > 0$  for  $A = y$ . If the  $MAC(A)$  curve is high enough, the  $MD(y - A)$  and  $MAC(A)$  curve would intersect at  $A^* < y$  i.e., socially optimal abatement would be less than privately optimal output and socially optimal net emissions would be positive. However, if the  $MAC(A)$  curve is lowered enough by reductions in marginal control cost or marginal cost of production,  $MAC(A) \leq MD(y - A)$  for  $A = y$  i.e., for all levels of abatement less than  $y$ ,  $MAC(A)$  would lie below  $MD(y - A)$  in the abatement-dollar space. Thus, the socially optimal levels of abatement and net emissions would be  $y$  and 0 respectively. However, given Proposition 1, the social optimum would correspond to a positive level of control and positive output less than  $y$ .

Let us now look at the case where  $MCC(0) > 0$ . We also assume  $MD(y - A) = 0$  for  $A = y$ . The  $MAC(A)$  curve is the same as that derived in Figure 1 and the social welfare maximizing level of abatement is again given by the intersection of the  $MAC(A)$  and the  $MD(y - A)$  curve. If that intersection occurs at a level of abatement above  $\bar{A}$  (mentioned in case (b) of Proposition 1) then the reader can easily see that the result (i) of Proposition 2 will go through. If the MD curve is low enough it will intersect the  $MAC(A)$  curve below  $\bar{A}$ , as indicated in Figures 4a, which means that all abatement will be facilitated by reduction and the existing control technology will not be used. However, as pointed out, the level of  $\bar{A}$  will increase in the magnitude of  $MCC(0)$  till the former reaches  $y$  and then remains constant at that level; this means that the highest position of the MD curve consistent with abatement only taking place through ‘reduction’ is higher for greater  $MCC(0)$  below a certain threshold value. Let us now consider two phenomena:

(a) Any large enough upward revision of MD in this case can take the social welfare maximizing level of abatement beyond  $\bar{A}$ , thus implying that control starts being used for abatement: in Figure 4a the initial upward movement of the MD curve (from  $MD^0$  to  $MD^1$ ) results in the intersection between the MD and  $MC(A)$  still occurring on the portion coinciding with  $NMB(Y - A)$  curve, with all abatement taking place through reduction even though it increases from  $A^*$  to  $A^{**} < \bar{A}$ ; however the second upward movement in the MD curve ( $MD^1$  to  $MD^2$ ) results in a positive level of control being used with a further increase in abatement to  $A^{***} > \bar{A}$ .

(b) When  $MCC(0)$  declines this results in a reduction in  $\bar{A}$  and the  $MAC(A)$  curve changing from  $MAC^0$  to  $MAC^1$  as indicated in Figure 4b, with the part coinciding with the  $NMB(A)$  curve becoming shorter and the other part shifting downwards. Note that if the initial level of  $A^*$ , the socially optimal level of abatement, is very low to start with (i.e.,  $A^* \ll \bar{A}$ ), this change might initially still be associated with no change in the socially

optimal level of abatement: see Figure 4b where the initial shift in the portion of the MAC curve associated with both positive reduction as well as control is small enough for the intersection to still be at the same point on the portion that coincides with the  $NMB(Y - A)$  curve. Thus, initial small improvements in control technology will not get manifested in any positive use of control. However, with subsequent improvements and shrinkage in the level of  $\bar{A}$  this situation will change and a positive use of control will ultimately result, as manifested in the change in the socially optimal level of abatement to  $A^{**}$  in Figure 4b. This is illustrated by the intersection between  $MAC^2$  and MD curves.

Our results can be summarized by the following proposition.

**Proposition 4:** *When  $MCC(0) > 0$ , the  $MAC(A)$  curve consists of two potential segments, the initial part coinciding with  $NMB$  which always exists, and possibly a second part given by the marginal expenditure on abatement when reduction and control are chosen to equate  $NMB$  and  $MCC$ . Consider  $MD(y - A) = 0$  for  $A = y$ . If the MD curve is high enough and therefore intersects the  $MAC(A)$  curve on the second part then all the results derived in Proposition 2 go through. If MD curve is low enough then the intersection takes place on the first part of the  $MAC(A)$  curve and abatement is just given by reduction with the existing control technology not being used. Small enough upward movements in the MD curve or a decrease in  $MCC(0)$  which result in the intersection still taking place on the first part of the  $MAC(A)$  curve imply that control technology remains unused, and there is no change in abatement in the case of the mentioned decrease. It is only for large enough shifts of the MD or MCC curves of the mentioned nature that a positive use of the control technology emerges.*

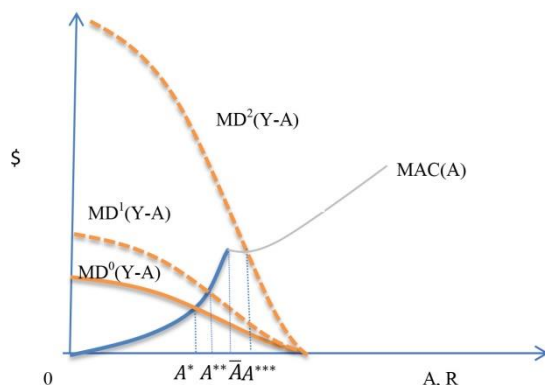


Figure 4a. Change in Socially Optimal Abatement for Upward Movement in the MD curve when  $MCC(0) > 0$  and  $MD = 0$  for Zero Net Emissions

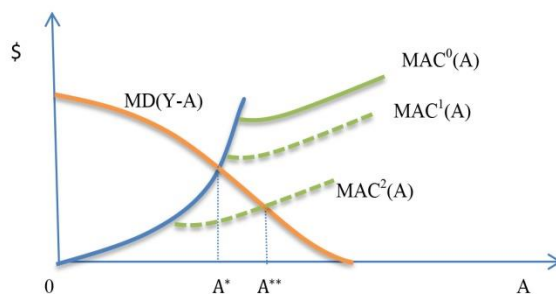


Figure 4b. Change in Welfare Maximizing Abatement When  $MCC(0) > 0$  with Decline in  $MCC(0)$  Causing Shift in  $MC(A)$  curve

Consider  $MCC(0) > 0$  and  $MD(y - A) > 0$  for  $A = y$ . In this case,  $MD(y - A)$  for  $A = y$  higher than  $MAC(y)$  will imply that socially optimal abatement would be equal to the privately optimal output. If in addition,  $MCC(0) > NMB(y - A)$  for  $A = y$ , socially optimal production of output would be 0. If this inequality is reversed, through say reduction of production cost, then some amount of output less than the privately optimal level would be produced and control equal to the actual level would be undertaken.



#### 4. Conclusion

The contribution of this paper lies in deriving socially optimal abatement (pollution avoidance) explicitly from separate technologies for production as well as control, where ‘control’ refers to decomposition of pollutants into harmless matter. This would help to construct welfare maximizing interventions, such as Pigouvian taxes, given that a firm can respond to such an intervention by reducing its output and undertaking control. To put it precisely, socially optimal abatement consists of (i) ‘reduction’ of output from its privately optimal level and (ii) ‘control’. Two cases, whose study yields valuable properties of socially optimal abatement and its mentioned constituents, are considered: marginal cost of control equal to zero at zero level of control, and positive marginal cost of control at zero level of control. These alternative assumptions are combined with the assumptions of marginal damage from emissions equaling 0 or exceeding 0 at zero emissions.

The findings of this paper are echoed by reality. For example, as pollution has increased in the cities of developing countries and households have become more aware of the damage from pollution, the perceived marginal damage from poor air quality in the house has gone up. At the same time, there has been an improvement in the technology for air purification. As predicted by the paper, casual empiricism shows that firms and households are finally investing in ‘control’ by buying air purifiers, which is attributable to efficiency of these purifiers crossing a threshold and greater awareness of the damages from air pollution.

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