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The Timing of Pollution Abatement Investments and the Business Cycle: an international comparison

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Abstract

In this paper we develop a simple equilibrium business-cycle model for an economy with both clean- and dirty-producing plants. We derive that the optimal timing of cleaning the production process is during a slowdown of the economy. Due to external effects and market failures the timing of pollution abatement investments is not expected to be optimal in the real world. We test the optimality of the timing of those investments with data for Germany, the Netherlands and the U.S.A. It appears that for more than 25 percent of the sectors pollution abatement investments show counter-cyclical behaviour, while in only one sector these investments are pro-cyclical.

Keywords: business-cycle model, pollution abatement investments, cleaning production, environmental regulation.

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1. Introduction

Governments are often reluctant to attack environmental problems in recessions. They argue that they have to wait untill the economy booms again, since then there is more "space" for action. In this paper, we argue that the best time to clean the environment is when the economy is slowing down, since the opportunity costs of cleaning the environment are lowest then. From the fifties until the beginning of the seventies, the conventional wisdom was that during recessions the economy should be stimulated through an increase of government spending. The arguments used then, differ however from ours. We believe that the government should concentrate the implementation of certain public projects in recessions, but only those which are necessary for long-run growth, such as investments in infrastructure and environment. Our motivation is not to dampen output fluctuations per se, but rather to concentrate investment activities in times when the opportunity costs of doing so are lowest.

There is some evidence (see e.g. Bean, 1990 and Saint Paul, 1993), that in recessions firms engage in activities that increase long run growth at the cost of a temporary fall in production. The reason for this is that the opportunity costs of those productivity increasing activities are lowest in recessions. With pollution abatement investments, things are more complicated, since the main reason for firms to undertake such investments is because they are forced to do so by the government. So, only when the government announces abatement laws early enough, firms will have the possibility to time their investments optimally.

In this paper we will first develop a simple model in which there are both clean and dirty plants. In this model, the consumer workers derive positive utility from consumption and leisure and negative utility from pollution. Dirty plants can be made clean but this has costs in the form of foregone production. Since most economies are growing over time it is necessary to continuously implement cleaner production techniques to keep the absolute amount of pollution constant. We will Capture this feature in our model by letting, in each period, revert some clean plants into dirty ones. We will show that in this model it is socially optimal to increase pollution abatement expenditures in periods when aggregate demand is low.

Even when the government takes account of pollution externalities by internalizing them in the prices or by setting emission standards the optimality result will only carry over to a decentralized market economy when there are no market failures like for example capital rationing. Otherwise, there is a potential role for governments to subsidize pollution abatement policies in recessions. The potential scope for government action, i.e. the importance of possible market failures, can only be assessed from an empirical investigation. We have therefore collected data on pollution abatement investments in different sectors for the U.S., Germany and the Netherlands. We look for a business-cycle effect in the ratio of abatement investment to total investment. For 70 percent of the country-sectors we do not find a cyclical pattern. A possible reason for this might be that the timing of environmental regulation itself is non-optimal. Another reason could be that we have used sectoral data rather than data on the firm level. In all but one of the sectors that do show a significant cyclical pattern of pollution abatement investments we find that, relative to total investment, those investments are counter-cyclical.

2. Theory

2.1 Model

We consider an economy with two production technologies, a clean-production technology and a dirty-production technology[1]. At the beginning of period t, S, infinitely lived consumer-workers are matched to clean-production sites, each producing output Y,. So, there is only one (variable) input factor in production. For simplicity, we distribute all workers over the unit interval. So, there are 1-S, workers matched to dirty-production sites, producing output Y_D, where $Y_D \geq Y_S$ if there have to be placed restrictions on the production technique to produce cleaner and $Y_D < Y_S$ if clean plants produce the same output with less resources. Note that the problem does not become trivial in the latter case in the sense that all workers will be matched to the clean-production sites (S, = 1), because such a transfer will not be costless due to operation costs. Let σ_t be the fraction of clean-producing sites that revert to dirty-producing sites within period t. This can for example be a consequence of depreciation. This process captures the idea that a constantly growing economy needs to continuously clean up the production process in order to keep the same absolute level of pollution.

Let Θ_t be the fraction of workers who move from dirty- to clean-production sites in period t. Then the law of motion for state variable S, is given by:

$$S_{t+1} = (1 - \sigma_t)S_t + \Theta_t(1 - S_t + \sigma_t S_t) \tag{1}$$

The first term in this equation gives the number of cleans which remain clean and the second term gives the fraction of old dirties plus new dirties which become clean-production sites in the next period. Finally, we will assume that there are operation costs involved for a worker who moves from a dirty-production site to a clean-production site. These costs are equal to one unit of time input by one (dirty-producing) worker. We can give three interpretations for these costs:

(1) The worker's time cost of moving from a closed dirty plant to a new clean plant. According to

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[1] This model draws on Davis and Heltiwanger's (1990) "prototype" model of job reallocation

this interpretation, unemployment is a direct consequence of cleaning the environment.

(2) An adjustment cost, in the form of foregone production caused by the opening of a new (clean) plant or the transformation of a dirty plant into a clean plant.

(3) An investment in human capital by the worker and site owner. It may for example be necessary to train the workers to work with the new cleaner technology. The costs of this investment are foregone production, since when a worker is being trained he cannot produce.

Now, for a given σ_t, there has to be made a decision about the fraction of workers at dirty-production sites who will be moved to clean-production sites, arriving at the beginning of period t + 1. To keep things tractable, we will assume that it is always possible to transform dirty- into clean-production sites. We can interpret σ_t now not only as the rate at which existing clean plants revert to dirty ones, but also as the rate at which clean-production techniques become available.

Let P_t represent a pollution index in period t given by:

$$P_t = \mu(1-\Theta_t)(1 - S_t + \sigma_t S_t) Y_D \tag{2}$$

We assume for.simplicity that clean plants do not pollute. So P_t is a function of the number of dirty-production sites. Now, let the utility function of all consumer-workers in period t depend on consumption and pollution, and be given by: $U(A_t C_t, B_t P_t)$. Where:

$$U_C > 0, \quad U_{CC} < 0, \quad U_P < 0, \quad U_{PP} < 0, \quad U_{CP} = U_{PC} = 0$$

A_t and B_t are utility shifters. A change in A_t will be interpreted here as an aggregate demand shock. B_t is a taste for the environment shifter. Furthermore, A_t, B_t and σ_t are assumed to follow first order Markov processes. We will assume the following functional form for utility:

$$U(A_t C_t, B_t P_t) = A_t \hat{U}(C_t) - B_t f(P_t) \tag{3}$$

Finally, it is assumed that consumers do not save. So aggregate consumption in period t is equal to aggregate production:

$$C_t = (1 - \sigma_t) S_t Y_S + (1 - S_t + \sigma_t S_t)(1 - \Theta_t) Y_D \tag{4}$$

Thus all income from both clean- and dirty-production sites is consumed. The opportunity costs of cleaning are in the form of foregone production and are represented by the term:

$$\Theta_t (1 - S_t + \sigma_t S_t) Y_D$$

At time t, a worker chooses a contingency plan that maximizes life time utility, given by:

$$\sum_{t=1}^{\infty} \beta^{t-1}\left[A_t \hat{U}(C_t) - B_t f(P_t)\right] \tag{5}$$

In what follows we will concentrate on the social plarmer's solution to the problem. Without govemment intervention there is no reason for the market sector to arrive at this solution, since there does not exist a market for pollution.

2.2 The social planner's problem

The social planner's problem can be formulated as a stochastic dynamic programming problem, with Bellman's functional equation given by:

$$V(S,A,B,\sigma) = \max_{\Theta \in [0,1]} \left[A\hat{U}[(1-\sigma)SY_S + (1-S+\sigma S)(1-\Theta)Y_D] - B\, f(P) + \beta E[\, V(\overline{S},\overline{A},\overline{B},\overline{\sigma})]\right] \tag{6}$$

$$\text{s.t. } \overline{S} = (1-\sigma)S + \Theta(1-S+\sigma S)$$

where overlined variables denote next period values.

For now, we are only interested in how the optimal policy function $\Theta(S,A,B,\sigma)$ reacts to innovations in A, B and σ. The first order condition of the maximization problem of (6) is given by:

$$A\hat{U}_C[(1-\sigma)SY_S + (1-\overline{S})Y_D]Y_D - Bf_P[\mu(1-\overline{S})Y_D]\mu Y_D = \beta E\left[\frac{\partial V(\overline{S},\overline{A},\overline{B},\overline{\sigma})}{\partial \overline{S}} \,\middle|\, A,B,\sigma\right] \tag{7}$$

Equation (7) tells us that under an optimal cleaning policy, the utility costs of foregone output, minus the utility gains from less pollution are equal to the expected utility gains resulting from an improved future environment (as a consequence of more clean-production sites) at the beginning of the next period.

It will be interesting to see how the number of workers moving from a dirty- to a clean-production site responds to a change in the number of currently employed clean-site workers. Therefore let us defme M, the number of workers who move:

$$M_t = \Theta_t(1 - S_t + \mathrm{US},) \tag{8}$$

thus:

$$\frac{\partial M}{\mathrm{a}\,S} = -(1-\sigma)\Theta$$

Since $\frac{\partial \overline{S}}{\partial S} = (1-\sigma) - (1-\sigma)\Theta$, we can write

$$\frac{\partial M}{\partial S} = \frac{\partial \bar{S}}{\partial S} - (1 - \sigma) \qquad (9)$$

The first part of the r.h.s. of (9) is similar to the consumption smoothing effect. The response to a positive wealth shock is not to consume everything at once but to invest part to increase future consumption. So if S increases (i.e. $\partial \bar{S}/\partial S > 0$, because for example σ is low) output in that period will be higher because less reallocation has to take place. Part of this higher output will, however, be used to improve future environment by moving more workers to clean-production sites now. The second term of the right hand side of (9), gives us the direct effect of S on M. For a given Θ, an increase in S will reduce the necessity to open more clean-production sites.

To get a better understanding of the relationship between current consumption, current pollution, future consumption and future pollution, we can use (6) in combination with (7) to get[2]:

$$\frac{A\hat{U}_C - \mu B f_P}{E(\tilde{A}\hat{U}_C)} = \beta E\left[(1 - \bar{\sigma})\left(\frac{Y_S}{Y_D}\right) | A,B,\sigma\right] \qquad (10)$$

Equation (10) gives an expression for the stochastic marginal rate of transformation and tells us that more present consumption will be allocated to the future if:

(1) the expected rate at which cleans become dirty $\bar{\sigma}$ is low.

(2) the expected ratio of output in clean and dirty plants (Y_S/Y_D) is high

(3) the disutility from current pollution (μBf_P) is high

2.3 Leisure

In this section we will extend the model by allowing for leisure and by allowing the production function between the two sectors to vary. Now, a consumer-worker either works in a clean plant, or works in a dirty plant or is being reallocated. Workers employed in the different sectors and 'workers' who are being reallocated have different utility functions. Let these utility functions be given by $U^S(AC,BP,T - a_S)$ for those employed in the clean sector, $U^D(AC,BP,T - a_D)$ for those employed in the dirty sector and $U^R(AC,BP,T-a_R)$ for those being reallocated, where T denotes common available time, a_S denotes labour time in the clean sectors, a_D denotes labour time in the dirty-producing sectors and a_R denotes the time it takes to be reallocated. So, it is assumed that each consumer-worker has an equal share in aggregate consumption. Let, for $i=S,D,R$, $U^i(AC,BP,T-a_i)$ be given by:

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[2] For a derivation, see appendix A.

$$U^i(AC,BP,T-a_i) = A\hat{U}^i(C) + \bar{U}^i(T-a_i) - Bf(P) \tag{11}$$

Accordingly, we will define the production functions for the clean and dirty sector as $g_S(a)$ respectively g,(a) which give the output of working a hours in respectively the clean and the dirty sector. When working in the clean sector requires different skills than working in the dirty sector we can interpret the model as one where workers in different plants build up firm specific human capital and in which it is possible to move from the dirty to the clean sector at the expense of a period of learning during which period one cannot produce.

We will now interpret the costs of cleaning the environment in terms of foregone production, due to the time it takes for a worker to move from the dirty to the clean sector. We will interpret Θ_t as the probability for an individual dirty-producing worker to be moved to the clean sector, instead of the fraction of workers that switches from a dirty- to a clean-production technique. The problem now is to find a functional equation for the "representative consumer," since we have explicit diversity across firms and households. We can do this by weighting the utility functions for consumption and leisure, over the different sectors. The weights are given by: $(1-\sigma)S$, the number of workers in the clean sector, $(1-S+\sigma S)(1-\Theta)$, the number of workers in the dirty sector, and
$(1-S+\sigma S)\Theta$, the number of workers who are being reallocated.

The social planner's problem can again be formulated as a dynamic programming problem with Bellman's functional equation now given by:

$$\begin{aligned} V(S,A,B,\sigma) = \max_{a_s,a_D,\Theta} [\ &(1-\sigma)S[A\hat{U}^S(C) + \bar{U}^S(T-a_S)] + (1-S+\sigma S)(1-\Theta)[A\hat{U}^D(C) + \bar{U}^D(T-a_D)] \\ &+ (1-S+\sigma S)\Theta[A\hat{U}^R(C) + \bar{U}^R(T-a_R)] - Bf(P) + \beta E[V(\bar{S},\bar{A},\bar{B},\bar{\sigma})]\ ] \end{aligned} \tag{13}$$

s.t.

$$c = (1-\sigma)Sg_S(a) + (1-S+\sigma S)(1-\Theta)g_D(a)$$

$$\bar{S} = (1-\sigma)S + \Theta(1-S+\sigma S)$$

$$P = \mu(1-\Theta)(1-S+\sigma S)g_D(a)$$

In appendix B it will be shown that the first order condition with respect to Θ implies that:

$$\begin{aligned} &[\ A(\hat{U}^D(C) - \hat{U}^R(C)) + (\bar{U}^D(T-a_D) - \bar{U}^R(T-a_R))\ 1 + g_D(a)A[(1-\sigma)S\hat{U}^S{}_C(C) + \\ &(1-\Theta)(1-S+\sigma S)\hat{U}^D{}_C(C) + \Theta(1-S+\sigma S)\hat{U}^R{}_C(C)] - g_D(a)\mu Bf_P(P) = JE\left[\frac{\partial V}{\partial \bar{S}}|A,B,\sigma\right] \end{aligned} \tag{14}$$

The first term between square brackets at the left hand side of (14) represents the change in current utility, in terms of leisure, of being in the reallocation mode instead of working in the dirty sector. The second term on the left hand side of (14) represents the marginal utility of consumption derived from working a units of time in the dirty sector, when output is shared between workers in the clean sector, workers in the dirty sector and workers being reallocated, while the third term represents the disutility of marginal pollution. The latter two terms can also be interpreted as representing the utility losses in terms of foregone output due to moving a worker plus the utility gains due to an improved environment caused by decreased production. The right hand side of (14) gives the expected utility gains resulting from an improved future allocation of labour. Thus equation (14) tells us that when Θ is chosen optimally[3], the utility losses, caused by moving a worker from the dirty to the clean sector, (including the (temporary) environmental gains of this action, caused by the fall in production), are equal to the expected utility gains resulting from an improved future environment.

(13) has the following implications for leisure[4]:

$$(1-\sigma)Sg_S'(a)A\hat{U}^S{}_C = \bar{U}^S{}_{(T-a_S)} \tag{15}$$

$$(1-S+\sigma S)(1-\Theta)g_D'(a)A\hat{U}^D{}_C - Bf_P(P)\mu g_D'(a) = \bar{U}^D{}_{(T-a_D)} \tag{16}$$

Equations (15) and (16) tell us that, at an optimal solution, the marginal utility of consumption derived from working one additional hour in the clean or in the dirty sector should be equal to the marginal utility of leisure in the corresponding sector.

A problem with the model above, is that one is either in one sector or in another or being reallocated, while it would be more realistic that labour supply decisions would vary over the three states. Townsend (1990) shows elegantly how one could do, this while maintaining the setup of a representative consumer.

2.4 Demand and technology shocks

Demand shocks

When A falls, the utility of consumption decreases, and it will be optimal to transform more dirties into cleans (optimal Θ increases) and hence more workers will be reallocated from dirty to clean plants. More cleans are opened because the marginal utility costs of foregone production, given by the l.h.s. of (7), are lower when aggregate demand, A is lower. An increase in Θ, will, according to (8) lead to an increase in the number of movers, M, by $(1-S+\sigma S)$ times the change in Θ.

In the model with leisure the same arguments hold. Equation (14) shows that a fall in A decreases the opportunity costs of cleaning the environment. But now we also see from (15) and (16) that there will be substitution from both the clean and the dirty sector into leisure.

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[3] Our assumptions are sufficient to ensure an interior solution.

[4] A derivation of (15) end (16) can be found in appendix B.

Technology and allocation shocks

First, consider an unexpected increase in σ; this is similar to a decrease of the number of clean sites, S. If the innovation in σ is considered to be persistent, the marginal rate of transformation (from future to current consumption) will fall, see equation (10). As a result, less current consumption will be sacrificed for an improved future environment.

An alternative form of an allocative disturbance, is an increase in the ratio Y_S/Y_D, for example due to a new energy saving technology. This will according to (10) lead to substitution from current consumption to reallocation activity resulting in higher future consumption and a cleaner environment.

3. Evidence

In environmental economics, theory seems to be ahead of empirics. While the implications of environmental degradation, environmental policy and resource restrictions have been analysed in many economic frameworks (e.g. growth, trade, public finance), there has been scarce attention for the estimation of the effects theory predicts. The main reason for this is of course not a lack of interest, but a lack of data. While there is a growing attention for economic data on environmental policy and its effects, this has not yet materialized in internationally available and reliable data.

In this section we present the results of an attempt to test one of the outcomes of our theoretical model. We look for a business-cycle effect in series of pollution abatement capital expenditures (PACE) in industrial sectors of Germany[5], the Netherlands and the USA. The series contain yearly data and cover the period between 1971 and 1991. A short description of the data and their sources can be found in appendix C.

The effect of the business cycle on PACE might be obscured when abatement technology is partly embedded in newly acquired capital. For this so-called *integrated* abatement technology, the assumption made in the model that the adjustment cost of installing new abatement capital is lowest during recessions, will probably not hold. In order to immunize the effect of integrated technology, and to concentrate on end-of-pipe technology, we used (the logarithm of) the ratio of PACE to total gross investment, rather than PACE itself, as the dependent variable. As a consequence, the hypothesis we test is not whether PACE is counter-cyclical, but whether it is *more* counter-cyclical (less pro-cyclical) than total investment.

The business-cycle indicator is the detrended, real sectoral output (in log's). We detrended the output series using a Hoderick-Prescott filter, with λ -the 'shadow price' of non-linearity- set to 100.

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[5] Germany is the territory of former West-Germany.

The HP-filter is a means by which a trend can be estimated that minimizes residuals, subject to a linearity constraint.[6]

We tested for unit roots in the series. For both the PACE-investment ratio series and the detrended output series the null hypothesis of a unit root could not be rejected in many cases. Hence, in the regressions the first difference of the (logarithm) of the series was used, which was indeed stationary in all cases. The regression equation was estimated using OLS. The resulting coefficients - which can be interpreted as the business-cycle elasticity of the PACE ratio - are presented in table 1.

It can be seen from table 1 that for 5 out of 30 estimations the business-cycle elasticity was significant on the 5 percent level. For another 4 estimations it was significant on the 10 percent level. Of these significant elasticities all but one have negative sign, indicating a counter-cyclical pattern.

The results show important cross-country asymmetries. The evidence suggests that the German PACE-investment ratios have the most manifest counter-cyclical pattern. For 40 percent of the German sectors the results show a counter-cyclical effect, where for the Dutch and American industrial sectors this figure is 20 percent. Moreover, for one Dutch sector (notably wood and wood products) a *positive* elasticity was found, suggesting that PACE in this sector are more pro-cyclical than total investment.

It is hard to detect a pattern in the sectors with significant coefficients. The only sector with significant results for more than one country is electrical goods (383), were for both the Netherlands and the USA a significant elasticity was found. This could imply that the timing of abatement investment is dominantly influenced by national factors, such as the method of regulation (ie taxes, laws, covenants) or the compliance time-schedule imposed by the regulator.

For many sectors, especially basic metal and metal products, the estimations did not yield significant results. Therefore the outcome of our model is not unambiguously supported. There can be many reasons for this. Besides technical reasons, like the disputable quality of the PACE series, an important reason is possibly that the predicted counter-cyclical nature of environmental investments is the result of a model where environmental policy is set by a 'social planner'. The observed pro-cyclicality of PACE in the Dutch wood sector could therefore be explained by non-optimal timing of the deadlines in environmental programs. If firms have to comply with regulation within a period where no recession occurs, they are forced to invest on a non-optimal moment in time. There is one other possible explanation that deserves attention. This has to do with the fact that we had to use sectoral rather than firm data. It may well be the case that at the firm level, PACE increases after a negative demand shock but that this does not carry over to sectoral level. Especially when firms are very heterogeneous and are mainly hit by idiosyncratic shocks this sort of bias will be severe (see also Caballero, 1992 on this issue).

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[6] See King and Rebelo (1993) for a description of the HP-filter, as well as its pros and cons

4. Conclusions

In this paper we showed that in a perfect working market economy, where all external effects are internalized in the prices and which faces both demand and technology shocks, the best time to undertake activities that improve the future environment at the cost of current output and consumption is in recessions. The reason for this is that the opportunity costs of doing so are lowest then. A priori there is no reason for this result to carry over to the real world. First of all there is no price for a clean environment, so the government should impose restrictions on the production process, which is indeed already done in many countries. But even when a government is able to define an optimal level of pollution and announces it at the right time, there may still be many market imperfections like e.g. imperfect information and credit rationing, which prevent firms from timing their pollution abatement investments optimally.

To get a better view of the relevance of those market imperfections we have therefore collected sectoral data on pollution abatement investments for a number of countries. We find that in more than 25 percent of the sectors the pollution abatement investments-total investment ratio depends negatively on the business cycle, while only in the Netherlands there is one sector in which this ratio moves procyclical. This result suggests that there is a potential role for government intervention. This first inquiry into the cyclical behaviour of environmental investment raises as many questions as it answers. Future empirical research should therefore focus on a better way to differentiate in the data between integrated and end-of-pipe technology, and address the question of how the sectoral and country differences can be explained. The latter topic would involve scrutinizing the environmental policy in different sectors and countries, assessing its time structure and the nature of the abatement technology it triggers.

Table 1. Estimates of the effect of the business cycle on the PACE-gross investment ratio, in the manufacturing sector of the Netherlands, Germany and the USA.

			elasticity	
Sector	**ISIC**	**Netherlands**	**Germany**	**USA**
food and tobacco	31	4.84 (1.17)	-3.83** (-1.90)	-5.36 (-1.10)
textile and leather	32	-3.01 (-.220)	-10.2* (-7.01)	-.2.12 (-.571)
wood and wood products	33	15.6** (1.75)	2.38 (.769)	-0.958 (-.429)
paper products	34	4.80 (0.217)	-10.1* (-2.46)	-7.09 (1.16)
chemicals	35	-5.09* (-2.17)	-2.90 (-1.25)	-1.33 (-,790)
mineral products	36	6.03 (1.67)	-2.32 (-.879)	-4.58* (-2.09)
basic metal	37	.1.04 (.220)	1.03 (.487)	1.19 (1.08)
metal products	381	3.50 (.235)	1.85 (.487)	-1.47 (-.843)
industrial machinery	382	21.23 (1.39)	-3.39** (-1.84)	.874 (.400)
electrical goods	383	-14.3* (-2.04)	2.32 (.456)	-4.93** (-1.89)

NOTES: *t*-statistics between parenthesis. A single asterisk indicates significance at the 5 % level. A double asterisk denotes significance at the 10% level.

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Appendix A. Derivation of the stochastic marginal rate of transformation.

Off corners and under the optimal reallocation policy function, the value function, V, is differentiable in S with[7]:

$$\frac{\partial V(S,A,B,\sigma)}{\partial S} = A(1-\sigma)\hat{U}_C[C](Y_S-(1-\Theta)Y_D) + \mu B f_P[P](1-\sigma)(1-\Theta)Y_D$$

$$+\beta(1-\sigma)(1-\Theta)E\left[\frac{\partial V(\overline{S},\overline{A},\overline{B},\overline{\sigma})}{\partial \overline{S}}\,|\,A,B,\sigma\right]$$

where overlined variables denote next period values.

Dividing the above equation by Y_D and substituting (7) into this equation yields:

$$A(1-\sigma)\hat{U}_C[C]\left(\frac{Y_S}{Y_D}-(1-\Theta)\right) + \mu B f_P[P]\,(1-\sigma)(1-\Theta) + (1-\sigma)(1-\Theta)\left(A\hat{U}_C[C]-\mu B f_P[P]\right) = \left[\frac{\frac{\partial V}{\partial S}}{Y_D}\right]$$

So,

$$A(1-\sigma)\hat{U}_C[C]\frac{Y_S}{Y_D} = \frac{\left[\frac{\partial V}{\partial S}\right]}{Y_D}$$

Hence,

$$\beta E\left[\frac{\left[\frac{\partial V}{\partial \overline{S}}\right]}{Y_D}\right] = \beta E\left[\overline{A}(1-\overline{\sigma})\hat{U}_C[C]\left(\frac{Y_S}{Y_D}\right)\right]$$

Now, substituting (7) back gives:

$$A\hat{U}_C[C] = \beta E\left[\overline{A}(1-\overline{\sigma})\hat{U}_C[\overline{C}]\left(\frac{Y_S}{Y_D}\right)|A,B,\sigma\right] + \mu B f_P[P]$$

which can be rewritten as:

$$\frac{A\hat{U}_C[C]-\mu B\,f_P[P]}{E(\overline{A}\hat{U}_C[\overline{C}])} = \beta E\left[(1-\overline{\sigma})\left(\frac{Y_S}{Y_D}\right)|A,B,\sigma\right]$$

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[7] For a proof, see Lucas and Stokey (1989), ch 9.

Appendix B. Derivation of equations (14), (15) and (16).

Substitute the constraints of (13) into the objective function of (13). Note that:

$$\frac{ac}{ae} = -(1-S+\sigma S)g_D(a)$$

$$\frac{\partial P}{ae} = -\mu(1-S+\sigma S)g_D(a)$$

and

$$\frac{\partial \bar{S}}{\partial \theta} = (1-S+\sigma S)$$

The first order condition for Θ is now given by:

$$- (1-\sigma)SA\hat{U}^S{}_C(C)\ (1-S+\sigma S)g_D(a)$$

$$- (1-S+\sigma S)(1-\Theta)A\hat{U}^D{}_C(C)\ (1-S+\sigma S)g_D(a) - (1-S+\sigma S)[A\hat{U}^D(C) + \bar{U}^D(T-a_D)]$$

$$- (1-S+\sigma S)\Theta A\hat{U}^R{}_C(C)\ (1-S+\sigma S)g_D(a) + (1-S+\sigma S)[A\hat{U}^R(C) + \bar{U}^R(T-a_R)]$$

$$+ Bf_P(P)\mu(1-S+\sigma S)g_D(a) + \beta E\left[\frac{\partial V}{\partial \bar{S}}\right](1-S+\sigma S) = 0$$

Rearranging and dividing by $(1-S+\sigma S)$ gives (14).

(15) and (16) can be found by looking at the f.o.c. from (13) for a_S and a,. First note that:

$$\frac{dU^S(AC,BP,T-a_S)}{da_S} = (1-\sigma)Sg_S'(a)A\hat{U}^S{}_C - \bar{U}^S{}_{(T-a_S)}$$

and

$$\frac{dU^D(AC,BP,T\text{-}u,)}{da_D} = (1-S+\sigma S)(1-\Theta)g_D'(a)A\hat{U}^D{}_C - \bar{U}^D{}_{(T-a_D)}$$

Now the first order condition with respect to a_S gives:

$$(1-\sigma)S[(1-\sigma)Sg_S'(a)A\hat{U}^S{}_C - \bar{U}^S{}_{(T-a_S)}] = 0$$

Hence,

$$(1-\sigma)Sg_S'(a)A\hat{U}^S{}_C = \bar{U}^S{}_{(T-a_S)}$$

which is equation (15).

The first order condition with respect to a_D gives:

$$(1-S+\sigma S)(1-\Theta)[A\hat{U}^D{}_C(1-S+\sigma S)(1-\Theta)g_D{}'(a)-\bar{U}^D{}_{(T-a_D)}]-Bf_p(P)\mu(1-\Theta)(1-S+\sigma S)g_D{}'(a)=0$$

Hence,

$$(1-S+\sigma S)(1-\Theta)g_D{}'(a)A\hat{U}^D{}_C-Bf_P(P)\mu g_D{}'(a)=\bar{U}^D{}_{(T-a_D)}$$

which is equation (16).

Appendix C. Data and Sources

The data on gross PACE are taken from national sources, since no deliberate, international survey of these data exist. Moreover, there are a mere handful of countries were PACE data of the private sector are collected in a consistent manner and over a longer period. The best data can be found for the Netherlands, Germany and the USA. Since these data are the result of national surveys, they cannot easily be compared. The dust has not yet settled on the discussion about the definitions and methodology that should ideally be used for abatement investment surveys. Recently, the EUROSTAT tried to synchronize the national bureaus of statistics of the EU by suggesting a common methodology by the name SERIEE, but it is unlikely that the German and Dutch survey will be altered to comply with these directions in the near future.

Apart from the disparities in definitions, cross-country comparison of the data is hindered by the different systems that are used for the sectoral breakdown. Each country employs a different categorisation. The German breakdown is based on the ***Systematik der Wirtschaftzweige, Fassung für Umweltstatistiken*** (SYUM), the Dutch CBS uses the ***Standaard Bedrijfs Indeling*** (SBI), the American Bureau of the Census based the sectoral breakdown on the ***Standard Industrial Classification*** (SIC). In order to facilitate cross-country comparison, we fitted the series in a common system of classification: the International Standard Industrial Classification (ISIC).[8]

The German series are from the Statistisches Bundesamt ***Investionen für Umweltschutz im produzierende Gewerbe,*** and cover the period from 1975 till 1991, on a yearly base. The Dutch data are from the Centraal Bureau voor de Statistiek ***Milieukosten van Bedrijven.*** The survey started in 1979, but estimations of PACE are available from 1971 till 1990. The Bureau of the Census publication ***Pollution Abatement Costs and Expenditures*** is the source of the American PACE series. The data range from 1973 till 1991. For 1987 no data are available.

Output and investment data are from the ***OECD Sectoral Database.*** Investment is gross fixed capital formation, output is real gross sectoral production.

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[8] An account of this mapping of classifications can be found in Bouman (1995). which also contains a more comprehensive description of the data.