Dynamic modelling of pollution abatement in a CGE framework

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Abstract

This paper deals with different specifications of pollution abatement in dynamic Computable General Equilibrium (CGE) models and analyses the influence of the different specifications on the dynamic feedback mechanisms between economic variables and abatement in the context of environmental policy.

The alternatives differ in the assumptions on the irreversibility of investment decisions concerning pollution abatement and the treatment of technological development. They share an explicit link between the bottom-up technical and economic information on abatement techniques and the top-down CGE-approach.

The practical suitability of the specifications is illustrated in the empirical application focussing on climate change and acidification. The analysis shows that the calculated costs of environmental policy is significantly influenced by the way abatement is specified. A good link between the bottom-up technical information on abatement techniques and the top-down economic model improves the understanding of the dynamic impacts of environmental policy on polluters and on the economy as a whole.

Keywords

Computable General Equilibrium models, pollution abatement, dynamics, tradable pollution permits

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1. Introduction

In order to make good estimations of the economic costs of environmental policy, the specification of the abatement costs, and of the underlying abatement technologies, is of utmost importance. On the one hand, standard CGE models use smooth, continuous production and utility functions and do not pay explicit attention to the characteristics of the abatement technologies involved. This is a common critique by mostly technically oriented scientists on these top-down economic models. On the other hand, most models that do take into account the technical aspects of changing economic structures do not model the indirect economic effects of these technologies (*i.e.* they adopt a partial framework). The large number of technological options available for pollution reduction complicates the use of discrete technology modelling in CGE models. Therefore, in this paper a different methodology is used in which the advantages of the top-down approach of CGE models are combined with the information on abatement technologies included in the bottom-up approach (for more details see Dellink, 2000).

The paper deals with different ways in which pollution abatement can be modelled in dynamic computable general equilibrium (CGE) models. The CGE approach is chosen because it provides a consistent framework to analyse the economic impacts of environmental policy: it has sound micro-economic foundations and a complete description of the economy with both direct and indirect effects of policy changes. There is a growing literature on dynamic CGE models for environmental policy analysis, ranging from e.g. Jorgenson and Wilcoxen (1990) to Böhringer (1998).

The set-up of this paper is as follows. In Section 2, the main CGE model is described. Section 3 deals with the specification of abatement with an emphasis on the dynamic characteristics of the abatement processes. Section 4 illustrates the model with a numerical example, analysing the dynamic impacts of climate change and acidification policies on the Dutch economy. Section 5 concludes. The appendices contain all the model equations (Appendix A1) and a description of the initial data (Appendix A2).

2. General description of the model

The model used in this paper is a dynamic computable general equilibrium (CGE) model with perfect foresight in the Ramsey tradition[1]. A more detailed description of the basic model is given in Dellink (2000), where this model specification is compared with other specifications of the dynamic issues. Here, only a general description of the model is given, focussing on the assumptions that are needed to build a multi-sectoral (dynamic) applied general equilibrium model, including a specification of environmental pollution and abatement activities. The full set of equations of the model is represented in Appendix A1.

Consumers (households) maximise their utility under a budget constraint, for given prices and given initial endowments. Producers (firms) maximise profits under the restriction of their

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[1] The forward-looking model has the advantage over recursive-dynamic models that consumers maximise their utility not only based on the current state of the economy, but also on future welfare (discounted to present values). This intertemporal aspect lacks in a recursive-dynamic model. Empirical estimates suggest that consumers in reality do look ahead to some extent, but do not maximise their utility till infinity (Srinivasan, 1982 and Ballard and Goulder, 1985). Intuitively, it is hard to imagine that none of the economic agents in the model takes a long-term view for his or hers decisions (Solow, 1974).

production technology, for given prices. Demand and supply, which result from the agents' optimisation problems, meet each other on the markets. In the current model version of the model, there is no international trade. This allows for an endogenous interest rate. The consumers own the production factors labour and capital (the endowments) and consume both produced goods (for which a CES-type utility function is used). The labour supply is fixed, but the wage rate is fully flexible; an exogenous growth of the labour supply is assumed. This growth in the labour supply drives the growth of the economy.

There is one representative private household and a government sector. The government sector collects taxes on all traded goods (both produced goods and the primary production factors) and uses the proceeds to finance public consumption of the two produced goods and pay for a lump-sum transfer to the private household. Furthermore, the assumption is made that government utility follows private utility (*i.e.* there is a constant ratio between the two levels of utility) throughout all model simulations by proportionately changing the existing tax rates.

Households maximise the present value of current and future utility, using the endogenous annual savings as one of the instruments. The budget constraint is only applied to the present value of all periods and not to individual periods, so that intertemporal borrowing of funds is assumed possible.

The capital stock and investment levels are fully endogenised: there are two additional fictitious production sectors modelled. The first, which may be called the capital services producer, transforms the current capital stock into capital services (that are input for the production sectors) and next period capital stock. The second fictitious production sector transforms investments by origin into next period capital stock. The consumers are endowed with a certain capital stock in the first period of the model and a final period capital stock (the transversality condition, in this case stating that capital stock in the last period should equal capital stock in the period before times the steady-state growth rate). The forward-looking behaviour of the agents and the endogenous savings rate make this model of the Cass-Koopmans-Ramsey type (Barro and Sala-i-Martin, 1995).

The nested-CES production function consists of the input of labour and capital and intermediate deliveries from the other producing sectors. Each producer produces one unique output from the inputs. As full competition is assumed, there are no excess profits to be reaped and the maximum-profit-condition diminishes to a least-cost-condition. The production function also contains the pollution associated with production and (the investments in) abatement by the sector.

Production processes lead to pollution, which is regarded as a necessary (environmental) input for the production functions. In the policy scenarios, pollution is controlled by the government by means of tradable 'pollution permits', that the producers (and consumers) can buy from the government (the proceeds are used to reduce existing taxes) [2]. In this way, a market for pollution permits is created, where, as in all markets in the model, prices are determined endogenously by equating demand and supply. Producers have the (endogenous) choice between paying for their pollution or investing in pollution abatement, and will always choose the least-cost of the two.

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[2] Practical difficulties may lead to a different choice of policy instrument in reality. Nonetheless, the approach taken here is the cost-effective one and can therefore serve as a reference point for evaluating other policy instruments.

By consuming, the households inevitably pollute. Just as producers, households can either pay for pollution permits or invest in abatement. A third possibility for producers (consumers) is a reduction of their production (consumption). This becomes a sensible option when both the marginal abatement cost and the price of the permits are higher than the value added foregone in reducing production (for producers) or utility foregone in reducing consumption (for consumers). Unless the level of required pollution reduction is very high, this is not likely to be a viable option.

Environmental quality is not directly included in the utility function, because it is assumed that the government sets the environmental targets by issuing a restricted number of pollution permits. Consumers' environmental expenditures (on pollution rights and abatement) do have an impact on the maximum consumption and utility level achievable, but environmental stocks and damages are not taken into account. In policy terms, the model cannot be used for Pigouvian analyses (Pigou, 1938), where the optimal tax rate is determined by the trade-off between abatement costs and damage costs, but rather for Baumollian exercises where the cost-effective way to reach a predetermined policy target is analysed (Baumol, 1977).

3. Description of the dynamic behaviour of abatement

3.1. Introduction

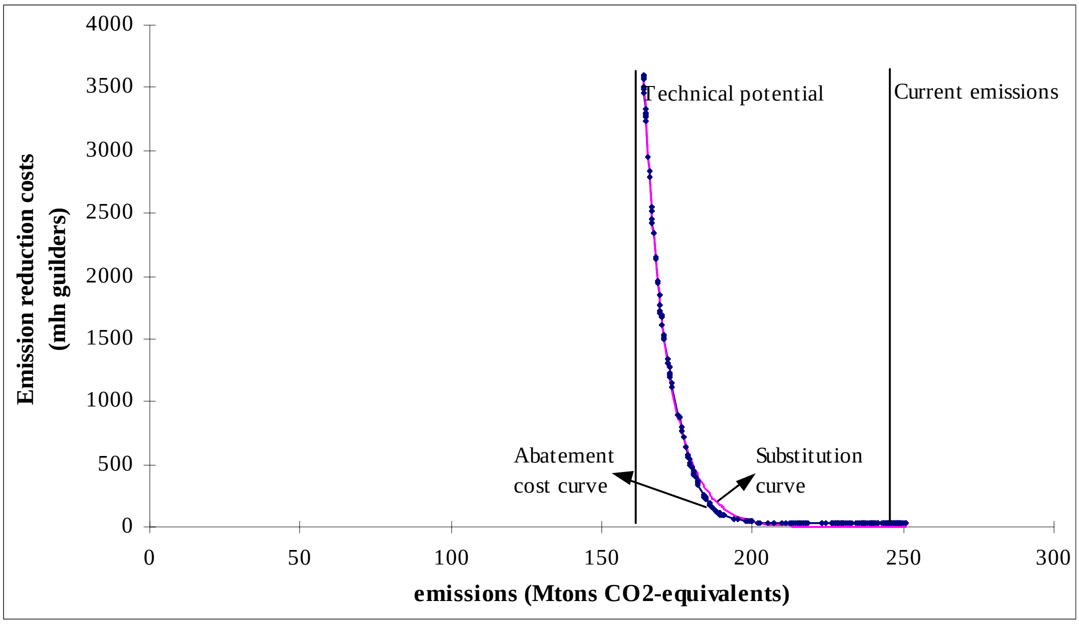
As mentioned above, polluters have the choice between paying for pollution permits or paying for abatement. The calibration of the possibilities and costs of abatement options is important to get a good estimate of the economic costs of environmental policy. In most literature, the abatement costs are only implicitly modelled (ref.), or modelled through a quadratic abatement cost curve (*e.g.* Nordhaus and Yang, 1996), though sometimes the specification of energy supply is more detailed (*e.g.* Manne *et al.*, 1995). Key exceptions are Nestor and Pasurka (1995) and Böhringer (1998). A key feature of the model presented here is that these expenditures on abatement are specified to capture as much information about the technical measures underlying the abatement options as possible.

As a first step in including the technical abatement information in the model, abatement cost curves have to be constructed for each environmental theme from the raw technical data. This step involves making an inventory of all available abatement options (both end-of-pipe and process-integrated options), ranking the measures by cost-effectiveness and solving some methodological and practical problems (including how to deal with measures that exclude each other and measures that have to be taken in a fixed order). For details on this first step see Dellink and van der Woerd (1997) and De Boer (2000a,b). Note that the abatement cost curves contain all known available options to reduce pollution, both end-of-pipe as well as process-integrated options (a.o. Pasurka, 2001, stresses the importance of process-integrated measures).

The abatement cost curves, which describe the marginal abatement costs, are translated for each producer / consumer and environmental theme into a 'substitution-curve' of pollution and abatement. This means that the abatement possibilities are presented as a function of pollution (a downward sloping curve). Then, a CES function is calibrated to best fit the substitution-curve. The CES-elasticity thus estimated describes the sector- and environmental theme-specific possibilities to substitute between pollution and abatement. The technical potential to reduce pollution through abatement activities provides an absolute upper bound on abatement in the model. This is a clear advantage over the traditional quadratic abatement cost curves, where no true upper bound on abatement activities exists (the abatement costs will always be finite, no matter how much pollution is abated). Dellink (2000) includes more details on this procedure, that combines the advantages of the CGE approach with technical and economic information on abatement techniques.

Figure 1 illustrates the concept of the abatement cost curve and substitution curve. Note that the x-axis gives pollution instead of pollution reduction. In the case of climate change, emissions in the Netherlands can be reduced from 251 megatons of CO_2-equivalents to 164 megatons CO_2-equivalents (given the current state of technology)[3]. Each mark on the abatement cost curve gives an individual technical measure; the line without markers shows the estimated substitution curve.

Figure 1. A substitution curve for greenhouse gasses



3.2. Abatement as a non-durable good

In this first specification, the abatement process is modelled as a separate producer, where ‘abatement goods’ are produced using both produced goods and primary production factors as inputs. This is roughly in line with Nestor and Pasurka (1995), but there the abatement sector is an implicit part of the government sector, and hence does not have a specific structure. In the model presented here, a CES production function is calibrated, for which the data are derived from abatement cost curves: the inputs in this production function represent the ‘spending effects’ of implementing technical measures. It is assumed that these spending effects are homogenous over the complete abatement cost curve and do not differ between the environmental themes. The model thus includes one producer (the abatement sector) to represent the abatement activities.

The output of the abatement sector is demanded by the other producers and by consumers, so each producer and consumer in principle has the same set of abatement technologies available. Each can however have differing substitution possibilities between investing in abatement and buying

[3] The graph and underlying data are based on analysis for 1990 and described in Verbruggen, 2000.

pollution permits. Consequently, both the marginal costs of abatement and the technical potential to reduce pollution through abatement will differ between the producers. The marginal abatement costs will be equalised in the model, as the resulting equilibrium is characterised by cost-effectiveness. These marginal abatement costs in the new equilibrium will also equal the price of the pollution permits. Hence, all polluters are indifferent at the margin between polluting and investing in abatement. The equations for the non-durable goods approach are represented in Appendix A1.

The model as described above assumes that expenditures on pollution abatement are completely reversible over time: if a sector spends money on abatement in period *t*, it can decide not to spend that money on abatement in period *t+1*. In other words, abatement is modelled as a flow variable, *i.e.* as a non-durable good, and decisions on abatement expenditures are short-term decisions (as opposed to abatement as a stock variable, where expenditures on abatement are long-term decisions). In the model, the term 'abatement goods' refers to the output of the abatement sector which is delivered to the polluters as a substitute for pollution. The value of these transactions denote the abatement costs. From theory it follows that the price of the abatement goods equal the marginal abatement costs. In the bottom-up technical description of the abatement measures, annual costs consist of capital costs, that is the interest and depreciation costs associated with investments, and net operational costs.

One consequence of the flow modelling of abatement is that there is no explicitly modelled development of investments in abatement capital. Even in this simple modelling of abatement, however, marginal abatement costs are changing over time. Since the abatement sector is a production sector like the other production sectors, the production costs of abatement goods are influenced by the general development of labour productivity[4]. As real labour costs become cheaper over time, so do the production costs of abatement. Consequently, if the production process of abatement is relatively labour-intensive the relative costs of abatement in comparison to other goods will decrease. Reversibly, if abatement is labour-extensive, the relative costs of abatement will increase over time[5]. Naturally, the prices of all goods that are input to the abatement sector will influence the real abatement costs, not only labour costs.

3.3. Abatement as a durable good

The second way abatement can be specified is through the modelling of abatement as a durable good. There are many examples of abatement measures that involve long-term decisions, including for example high efficiency boilers for consumers and flue gas desulpherisation installations in industry.

In model terms, firms demand abatement services, which are supplied by the abatement sector. This set-up is equivalent to the way the capital market is modelled. Drawing the analogy further, abatement investments (additions to the abatement stock), the abatement stock (the physical

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[4] In the model, increases in labour productivity are modelled through an increase in the supply of labour. Mathematically, this is equivalent. One can regard the labour supply as labour supply in efficiency units rather than in number of people.

[5] Empirical data suggest that in the Netherlands abatement is more labour-intensive than the other produced goods (labour makes up a little less than 50% of abatement costs; Dellink, 2000), and hence real abatement costs are decreasing over time.

abatement capital that last more than 1 period) and the abatement services (the annual use of the abatement stock) have to be modelled.

As in the flow-specification, only one common abatement sector is modelled. This means a homogenous abatement stock, investments and services. The model does not differentiate between agricultural, industrial, services' or consumer's abatement. The common abatement stock delivers abatement services to all sectors. This simplification is clearly beside reality, but a disaggregated specification of abatement is beyond the scope of the current paper, as it would require more data than is currently available (Verbruggen, 2000).

Assume $KA_{e,t}$ represents the stock of abatement for environmental theme *e* in period *t*, abatement services are given by $AS_{e,j,t}$ and investments in abatement by IA_t. Base period abatement stock is calibrated to the balanced growth path $KA_{e,0} = AS_{e,0} / (r_A + \delta_A)$, where r_A represents the opportunity costs of abatement (taken to be equal to the interest rate) and δ_A represents the depreciation of the abatement stock. This base period abatement stock is part of the endowments of the private consumers.

The production function for the 'abatement investment production sector' (IA_t) is based on the production function of the abatement sector in the non-durable goods specification:

$$IA_t = CES(Y^{ID}_{1,A,t}, ..., Y^{ID}_{J,A,t}, K_{A,t}, L_{A,t}; \sigma^1_A, ..., \sigma^V_A) \quad \text{for each } t$$

The output of this sector are additions to the sector-specific abatement stock $KA_{e,t+1} = KA_{e,t} \cdot (1-\delta_A) + \xi_e \cdot IA_t$, where ξ_e indicates the share of environmental theme *e* in the division of abatement investments (this share is endogenously determined within the model as the different sectors compete with each other for the scarce abatement investment goods). The sector specification of the abatement stock allows different abatement activities by the different sectors, but they all invest in their abatement stock from the common pool of abatement investment goods.

Every period the existing abatement stock provides abatement services: $AS_{e,j,t} = \psi_j KA_{e,t} \cdot (r_A + \delta_A)$ for producers and $AS_{e,h,t} = \psi_h KA_{e,t} \cdot (r_A + \delta_A)$ for consumers. The shares of the different sectors and consumers (ψ_j and ψ_h) are endogenously determined within the model, based on the market balance between supply and demand of abatement capital.

As with the capital stock, a transversality condition on the last-period abatement stock is required to avoid the abatement stock from falling to zero near the end of the time horizon. The transversality assumption used is that final period abatement stock is an asset for the private households, under the condition that last-period abatement stock equals previous period abatement stock multiplied by the steady-state growth rate $KA_{e,tlast} = (1+g) \cdot KA_{e,tlast-1}$. This condition also assures that investments in abatement will be at their steady-state level in the last period.

For man-made capital, investments come from household savings. When investments in abatement are added to the model, this implies that there are two destinations for savings: investment in man-made capital and investments in abatement. The proportion of savings that is invested in abatement is endogenous to the model, and is determined by the cost-effective behaviour of the agents. If environmental costs (the payments for environmental services) are high relative to capital costs, a larger portion of savings will be directed to abatement, leading to a higher supply of abatement services in future periods, thereby reducing the costs of abatement and hence reducing the expenditures on environmental services. The relevant equations for this approach are represented in Appendix A1.

The specification of abatement technologies as a stock does not imply that different assumptions are made with respect to technological development. In both specifications there is no explicit modelling of any development of marginal abatement costs over time (apart from the autonomous pollution efficiency improvement and the effect of labour productivity improvements over time). However, environment-oriented technological progress is implicitly endogenised in the model, since both the quantity of abatement services (through the endogenous savings for abatement) and the price of abatement (and environmental services in general) depend on the relative prices of the various goods.

3.4. A simplified vintage specification of abatement

From the discussion above it follows that in order to reflect reality as closely as possible, the specification of the model should contain both irreversibility in the adoption of abatement measures (captured through the durable goods specification) and technological change with respect to the marginal abatement costs over time. The latter issue can be dealt with by assuming that the services delivered by the abatement sector change over time. In order to capture this essential fact in the model, vintages of environmental services are modelled. These vintages reflect the changing marginal costs of abatement technologies over time.

To keep the model calculations tractable, the vintage approach is simplified by making the assumption that there is a basic difference between new and extant environmental services. All extant environmental services are represented by one (inflexible) production function. Given the fact that old abatement technologies contain a bundle of different possible technologies, there is still some room for substitution in the production function for the extant environmental services, though clearly the production function for new environmental services is more flexible. The most relevant equations for this simplified vintage specification are represented in Appendix A1.

New environmental services are a CES-combination of pollution (permits) and abatement services in efficiency units[6]: $ES^N_{e,j,t} = CES(E_{e,j,t}, \varphi^N_{e,j,t} \cdot AS_{e,j,t}; \sigma^{AN}_{e,j})$, where $\varphi^N_{e,j,t}$ gives the (normalised) state of technology ($\varphi^N_{e,j,tfirst} = 1$). An increase in $\varphi^N_{e,j,t}$ over time replicates the effect that (autonomous) technological progress will lead to decreasing abatement costs over time.

Extant environmental services are modelled similarly: $ES^O_{e,j,t} = CES(E_{e,j,t}, \varphi^O_{e,j,t} \cdot AS_{e,j,t}; \sigma^{AO}_{e,j})$

A logical choice for $\varphi^O_{e,j,t}$ is to assume $\varphi^O_{e,j,t} = \varphi^N_{e,j,t-1}$ (this implies that the extant abatement stock is as efficient as previous period's new abatement).

The producers demand total environmental services and do not differentiate between new and extant environmental services.

A fraction $(1-\delta)$ of the total environmental services 'survives' to the next period and becomes the extant environmental services for the next period: $ES^O_{e,j,t+1} = (1-\delta_A) \cdot (ES^O_{e,j,t} + ES^N_{e,j,t})$.

[6] Note the simplified notation for pollution; the full equation is given in Appendix A1.

As with other types of capital goods, a transversality condition has to be specified[7]:
$ES^N_{e,j,tlast} = (1+g) \cdot ES^N_{e,j,tlast-1}$, or equivalently $ES^N_{e,j,tlast} = (g+\delta) \cdot ES_{e,j,tlast-1}$.

Base period environmental services are given, and there is no need for distinction between new and extant environmental services in the first period.

For consumers, a similar set of equations are derived, where index *j* is replaced by index *h*.

The interpretation of the vintage specification is as follows. Once a certain combination of pollution and abatement is chosen by the polluters, they cannot change it later. The only way they can reduce pollution *ex post* is through the flexible new environmental services. The simplified vintage approach is based on the specification of the MERGE model (Manne *et al.,* 1995).

4. EMPIRICAL APPLICATION OF THE MODEL

4.1. Introduction

The model specifications described above are illustrated in this section with a numerical example. The numerical example is based on data for the Netherlands, with 2000 as the base year. Data sources are the national accounts (Statistics Netherlands, 2001) and environmental data provided by RIVM (2000). GDP equals 750 billion guilders and abatement expenditures amount to 12 billion guilders (excluding expenditures on waste management, which are assumed to be part of the services sector). The full set of data as used in calibrating the model for 2000 is given in Appendix A2. In interpreting the results one should keep in mind that the description of the economy is kept simple, with only 3 production sectors, no international trade, *et cetera*. Though these simplifications make the model results more tractable, the confidence to be placed on the numerical outcomes is limited. A full empirical analysis is beyond the scope of the current paper.

The base projection consists of an (autonomous) increase in labour productivity of 2% per year. This fuels a balanced growth of the economy of 2%. There is an autonomous pollution efficiency improvement of 1% per year, resulting in a growth of emissions of 1% per year.

All producers have a Cobb-Douglas production function for intermediate deliveries and primary factors. The substitution elasticity between abatement and pollution is set to 1.25 for climate and 1.4 for acid related emissions respectively (this value is based on Verbruggen, 2000). Investments are made up of agricultural and industrial goods and services in a ratio of 1:5:4. Private consumers have a utility function with a CES elasticity of 1 (Cobb-Douglas utility function); the corresponding elasticity for the government is set at 0 (Leontief' utility function). The intertemporal rate of substitution of consumption is set at 0.5. The depreciation rate is set at 7 percent and the interest rate at 5 percent.

The policy target is set at the 2000 level of emissions. Up to 2010, emissions can grow unrestricted, and thereafter the number of pollution permits issued by the government is kept constant at the new policy level[8]. For the delayed policy, the emissions are restricted only from

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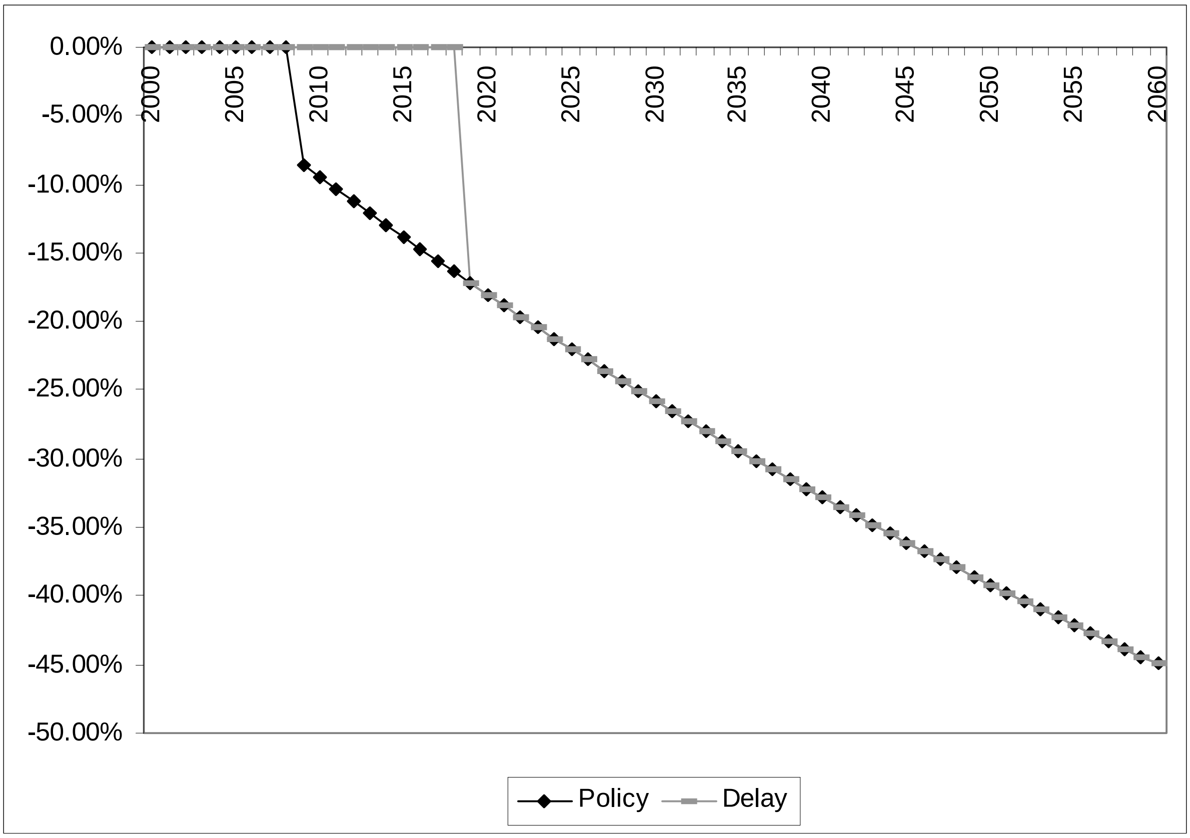
[7] Note the resemblance with capital and investments ($I_{SS} = (g+\delta) \cdot K_{SS}$): ES^N represents the 'investments' in 'environmental capital' *ES*.

[8] The environmental policy is not implemented in the first few periods, as the specification of abatement as a durable good implies that it takes several years to build up enough abatement goods to reduce emissions.

2020 onwards. As the emissions are rising in the base projection, the stabilisation policy leads to increasingly large differences between the number of permits issued and the reference emissions (which can be interpreted as the base demand for the permits). Figure 2 shows how the issued number of permits deviates from the base.

Figure 2. Effects of environmental policy on emissions (for both environmental themes)



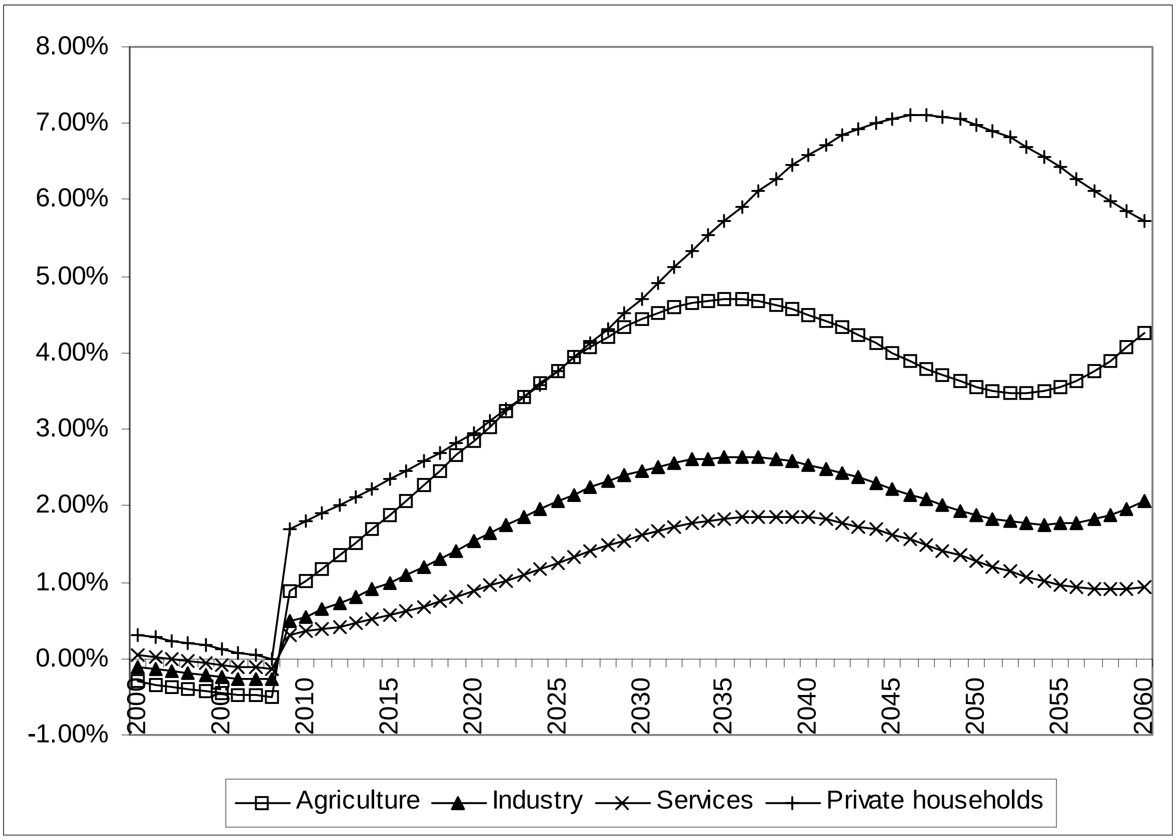
4.2. Abatement as a non-durable good

In the specification of abatement as a non-durable good, each year the polluters choose a new, optimal combination of buying pollution permits and buying abatement goods. Hence, it may be optimal to spend a relatively large amount of money on abatement in period *t*, and much less in period *t+1*. However, it should be noted that the specification of abatement as a non-durable good does not imply that the substitution possibilities are infinite: there is still a finite substitution elasticity between pollution and abatement. This prevents a situation where extremely large fluctuations in the demand for abatement occurs.

The results confirm that the demand for abatement goods is relatively stable over time. Figure 3 shows the development of the demand for abatement goods by the various polluters over time (for the Policy case). Up to the moment the environmental policy is introduced, the expenditures on abatement remain roughly in line with the base projection. In 2010, the year of introduction of the environmental policy, the abatement expenditures jump upwards and continue to grow thereafter. In qualitative terms, this mirrors the development in pollution levels. The size of the increase in abatement expenditures is however relatively small: for all sectors, it remains well below ten percent. This indicates that there is a significant part of the abatement cost curve that is relatively flat, *i.e.* a substantial part of emissions can be avoided by taking low cost abatement measures.

The sectoral differentiation of the abatement expenditures is primarily driven by the emission intensity of the polluters (emissions per unit of production or per unit of value added). For climate change, this intensity is highest for industry (mainly energy related), followed by agriculture (N_2O and methane emissions). For acidification, agriculture has the largest intensity (emissions of ammonia), followed by industry (again, mainly energy related). The figure shows these differences in intensity clearly. The largest increase in abatement expenditures is however observed for the private households, especially in the later periods. Then, investments are low and the households want to get as high consumption as possible and hence demand more environmental services.

Figure 3. Effects of environmental policy on the demand for abatement goods



Given the limited impact of the environmental policy on abatement expenditures, the effects on the rest of the economy are also expected to be limited. Table 1 shows that this is indeed the case: the impacts on GDP, consumption and production is in almost all cases less than 1%. In 2050, the agricultural sector is most negatively affected by the environmental policy, even though the consumption for agricultural goods is (slightly) above the base projection. The agricultural sector is relatively worse off on the one hand due to the relatively high pollution intensities in this sector (as discussed above), and on the other hand due to the absence of the positive indirect effect of higher demand for products by the abatement sector.

Table 1. Changes in main variables in the non-durable good case

(%-change in volumes)	Policy			Delayed policy		
	2010	2025	2050	2010	2025	2050
GDP	-0.20%	0.21%	-0.61%	-0.17%	0.30%	-0.53%
Private consumption of Agricultural goods	-0.29%	-0.38%	0.15%	-0.38%	-0.29%	0.21%
Private consumption of Industrial goods	-0.13%	-0.48%	0.50%	-0.22%	-0.43%	0.52%
Private consumption of Services	-0.03%	-0.38%	0.60%	-0.14%	-0.34%	0.61%
Sectoral production Agriculture	-0.47%	0.43%	-1.42%	-0.38%	0.56%	-1.28%
Sectoral production Industry	-0.27%	0.24%	-0.81%	-0.23%	0.33%	-0.71%
Sectoral production Services	-0.17%	0.12%	-0.40%	-0.17%	0.19%	-0.34%
Capital investment	-0.47%	1.69%	-3.28%	-0.15%	1.86%	-3.05%
Abatement expenditures	0.63%	2.07%	2.24%	-0.24%	2.17%	2.33%
Greenhouse gas emissions	-9.47%	-22.02%	-39.19%	0.00%	-22.02%	-39.19%
Acidifying emissions	-9.47%	-22.02%	-39.19%	0.00%	-22.02%	-39.19%

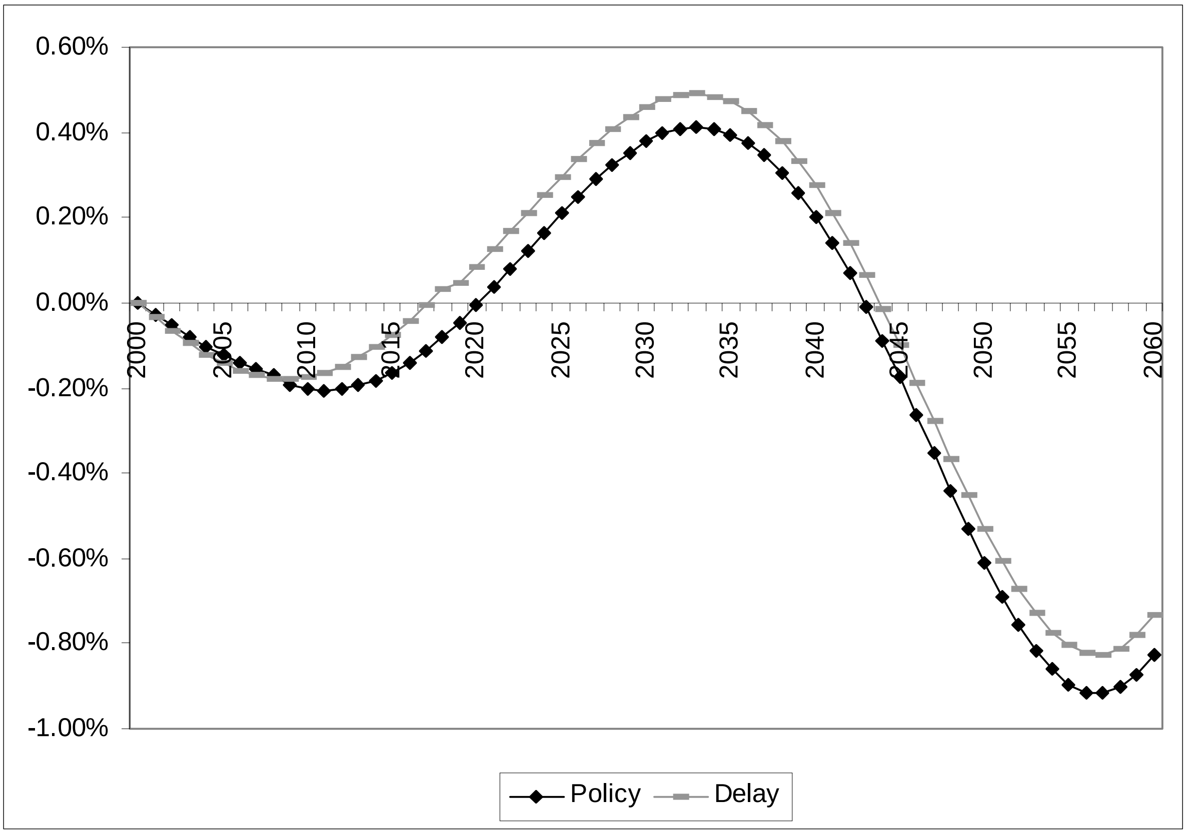
The consequences for the economy of a delay in the policy with 10 years are rather small. Even in the short run, the results between both simulations are comparable.

Table 1 shows that there are some cyclical effects of the environmental policy on the economy. This can more clearly be seen in Figure 4. A small reduction of GDP occurs in the years before the policy is introduced, followed by a minor fall in GDP in the year of introduction of the policy. This is a clear illustration of the anticipatory behaviour that is present in the perfect-foresight model. After introduction of the policy, GDP increases for 20 year and then rapidly declines. An explanation for this cyclical behaviour is that the discounted value of later periods is smaller than that of earlier periods. Consequently, it may be optimal to consume more in the earlier periods and accept a loss in economic growth and hence consumption in later periods.

Part of the cyclical behaviour is however caused by the introduction of the system of pollution permits: the base projection does not contain such a system, and pollution is free. If a system of pollution permits is introduced, the polluters will have to pay for their pollution, even though the number of permits issued is large enough to keep the base activities possible. The impact of this introduction is limited (below 1% for all periods for GDP), but certainly not negligible compared to the results of the policy simulations.

For the delayed policy, the picture is similar. In this case, GDP can increase above the policy level in the years of the delay (2010-2020), and this additional GDP can be sustained thereafter. The fact that the shock of introducing the policy is larger (see Figure 2) does not influence this, as polluters have (forward-looking) knowledge about the policy.

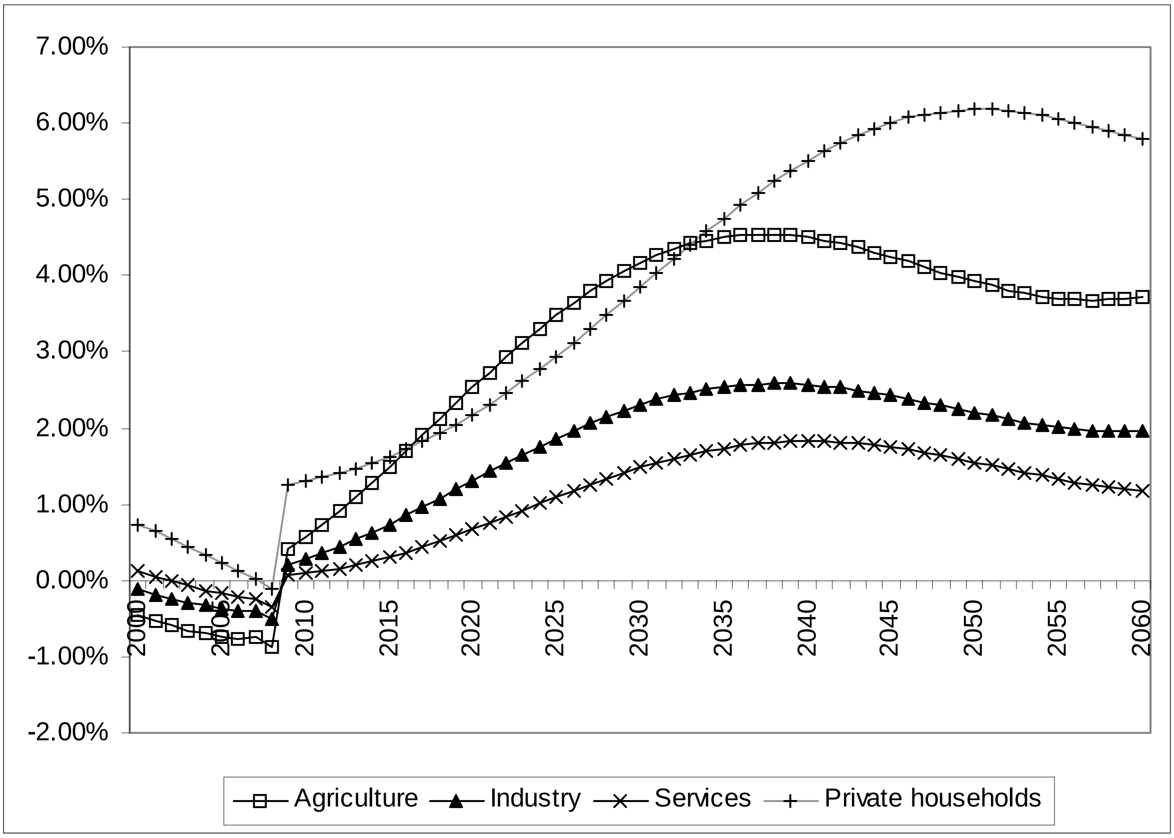
Figure 4. GDP-impacts in the non-durable good case.



4.3. Abatement as a durable good

For the specification of abatement as a durable good, the expectation is that it will be more costly to implement environmental policy in the short term, as there will be a limited possibility to accumulate abatement capital to avoid paying for the pollution permits. In the longer run, the effect is likely to be smaller, as the long-run flexibility of the system is larger in the durable good case. Figure 5 confirms this: expenditures on abatement services are smaller than in the non-durable case, but not much.

Figure 5. Effects of environmental policy on the demand for abatement services



In Table 2, the outcomes for main variables are represented. Comparing Table 2 with Table 1, the general picture emerges that the short-term economic costs of the environmental policy are larger in the durable goods case, but in the longer run, the main economic variables are all higher in the durable goods case. In fact, the negative impact of environmental policy on GDP and sectoral production levels in 2050, which occurs in the non-durable goods case, is mitigated in the durable goods case by higher investment levels in the short and medium term.

In the first decades, abatement investments rise above the base projection levels, and even more so than the abatement expenditures in the non-durable goods case. This indicates that in these periods, consumption is being sacrificed in order to build up enough abatement capital stock to be able to have enough abatement possibilities in later decades. In the later decades, there is less need for abatement investments, and they fall back to some extent. Though, clearly, there is still a significant amount of abatement investments needed to offset the depreciation of the larger abatement capital stock.

As the abatement stock cannot respond immediately to a higher demand for abatement services, the growth in abatement services is relatively low in the first periods. It is only slightly above the base projection, but below the abatement expenditures in the non-durable goods case. In the later decades the abatement investments pay off and the abatement capital stock, and its associated annual abatement services, can grow to levels above the abatement expenditures in the non-durable goods case.

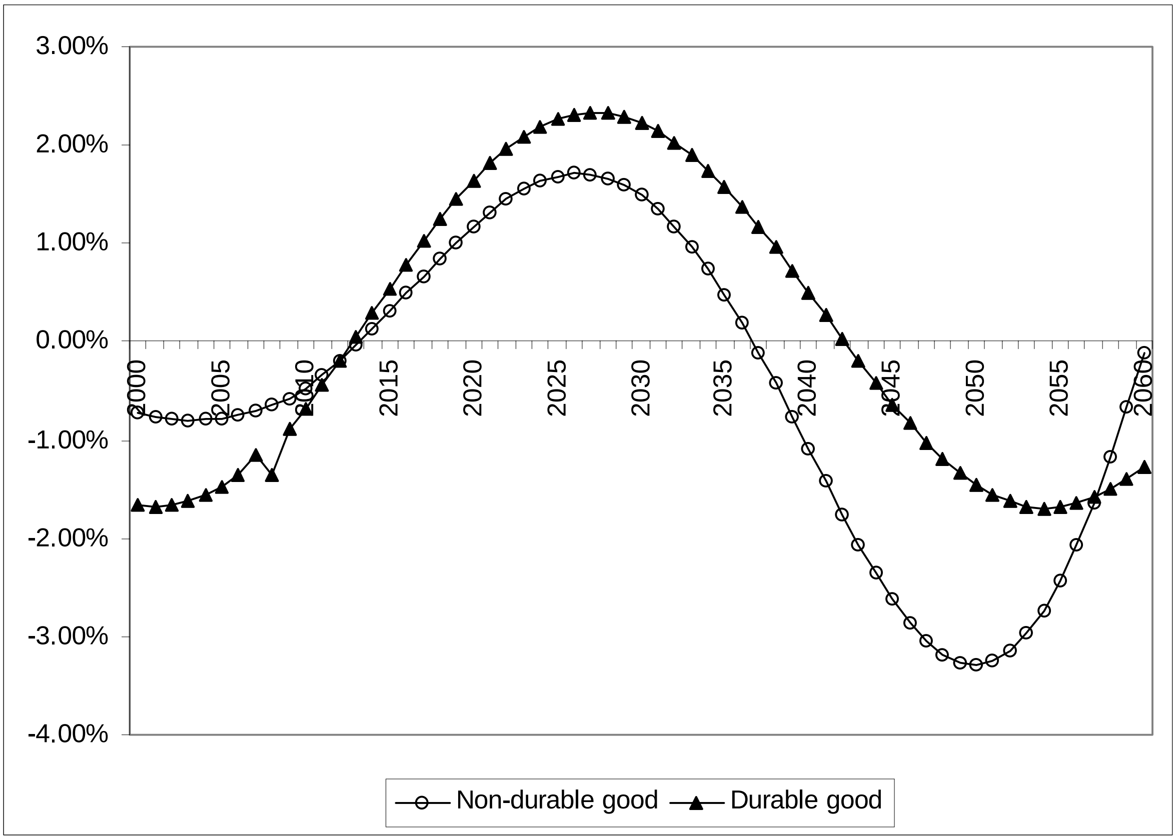
The delayed policy case shows a similar picture, with the main difference that in 2025, just 5 years after implementation of the delayed policy, the main economic variables are still below the levels of the non-durable goods case.

Table 2. Changes in main variables in the durable good case

(%-change in volumes)	Policy			Delayed policy		
	2010	2025	2050	2010	2025	2050
GDP	-0.38%	0.28%	0.05%	-0.39%	0.12%	0.12%
Private consumption of Agricultural goods	-0.55%	-0.47%	0.65%	-0.47%	-0.63%	0.71%
Private consumption of Industrial goods	-0.26%	-0.61%	0.66%	-0.19%	-0.69%	0.67%
Private consumption of Services	-0.21%	-0.54%	0.72%	-0.13%	-0.62%	0.73%
Sectoral production Agriculture	-0.67%	0.67%	-0.33%	-0.73%	0.43%	-0.20%
Sectoral production Industry	-0.40%	0.35%	-0.07%	-0.44%	0.20%	0.00%
Sectoral production Services	-0.33%	0.15%	0.15%	-0.33%	0.02%	0.21%
Capital investment	-0.67%	2.26%	-1.46%	-0.91%	1.93%	-1.24%
Abatement investments	1.09%	3.03%	1.98%	-0.47%	2.88%	2.08%
Abatement services	0.33%	1.83%	2.46%	-0.43%	1.67%	2.54%
Greenhouse gas emissions	-9.47%	-22.02%	-39.19%	0.00%	-22.02%	-39.19%
Acidifying emissions	-9.47%	-22.02%	-39.19%	0.00%	-22.02%	-39.19%

In Figure 6 the effects of the environmental policy on capital investments is represented for both the non-durable and durable good cases. In qualitative terms, both curves look similar, but there are significant differences. As expected, the fall in capital investments in the early periods is larger in the durable goods case, as some of these investments are crowded out by the abatement investments (remember that they compete for the savings by the consumers). This is made up in the third and fourth decade under analysis, when capital investments are higher than in the non-durable goods case. The development of capital investments has its impact on the development of GDP: in the first few periods, GDP is lower in the durable goods case, but in later periods it is structurally higher.

Figure 6. Effects of environmental policy on capital investments.



4.4. A simplified vintage specification of abatement

{Results for this specification are not yet available.}

5. CONCLUDING REMARKS

This paper shows how important characteristics of pollution abatement can be captured in a CGE framework. The extended calibration of the abatement possibilities is important, as it has significant effects on the estimation of the economic costs of environmental policies.

When environmental policy remains limited in size, there are cheap abatement options available, and the effect on the rest of the economy is minor. However, the more strict environmental policy becomes, the more significant it is to get the best possible representation of abatement possibilities. The macro-economic impacts of high marginal abatement costs can be significant.

It should be noted that many improvements to the model can be made, both in the specification of the model and in the calibration for empirical analysis. One major issue to be investigated in more detail is the possibility to capture endogenous technology. Clearly, price induced technological change is of the highest importance when one wants to specify pollution abatement as realistic as possible[9]. However, the empirical literature on these issues is still underdeveloped and it is

[9] For instance, a high price of pollution permits will most likely lead to innovations of new abatement technology, there are spill-over effects of general technological development to abatement technology, learning effects should not be ignored, *et cetera*.

beyond the scope of the current paper to capture these issues in all detail. Besides, the durable goods specification of abatement as presented in this paper provides endogenous balancing of investments in abatement capital and other capital and thus captures price-induced technological progress in a rudimentary way.

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APPENDIX A1. SPECIFICATION OF THE RELEVANT EQUATIONS

A1.1. Abatement as a non-durable good

Producers

Goods production functions:

$$Y_{j,t} = CES(Y^{ID}_{1,j,t},...,Y^{ID}_{J,j,t}, K_{j,t}, L_{j,t}, ES_{1,j,t},..., ES_{E,j,t}; \sigma^1_j,...,\sigma^V_j) \quad \text{for each } (j,t)^{10} \tag{1}$$

Zero profit conditions:

$$\begin{aligned} 0 = \Pi_{j,t} = \quad & p_{j,t}\cdot Y_{j,t} - \sum_{jj=1}^{J}(1+\tau_{jj,j})\cdot p_{jj,t}\cdot Y^{ID}_{jj,j,t} - (1+\tau_{A,j})\cdot p_{A,t}\cdot Y^{ID}_{A,j,t} \\ & -(1+\tau_{L,j})\cdot p_{L,t}\cdot L_{j,t} - (1+\tau_{K,j})\cdot r_{K,t}\cdot K_{j,t} - \sum_{e=1}^{E} p_{e,t}\cdot E_{e,j,t} \end{aligned} \quad \text{for each } (j,t) \tag{2}$$

Environmental services 'production' functions:

$$ES_{e,j,t} = CES(E^U_{e,j,t}, CES(E^A_{e,j,t}, A_{e,j,t}; \sigma^A_{e,j}); \sigma^{ES}_{e,j}) \quad \text{for each } (e,j,t)\text{, with } \sigma^{ES}_{e,j} = 0 \tag{3}$$

$$ES_{e,h,t} = CES(E^U_{e,h,t}, CES(E^A_{e,h,t}, A_{e,h,t}; \sigma^A_{e,h}); \sigma^{ES}_{e,h}) \quad \text{for each } (e,h,t)\text{, with } \sigma^{ES}_{e,h} = 0 \tag{4}$$

$$\left(E^A_{e,j,t+1}/Y_{j,t+1}\right) = (1-apei_{e,t+1})\cdot\left(E^A_{e,j,t}/Y_{j,t}\right) \quad \text{for each } (e,j,t) \tag{5}$$

$$\left(E^U_{e,j,t+1}/Y_{j,t+1}\right) = (1-apei_{e,t+1})\cdot\left(E^U_{e,j,t}/Y_{j,t}\right) \quad \text{for each } (e,j,t) \tag{6}$$

$$\left(E^A_{e,h,t+1}/W_{h,t+1}\right) = (1-apei_{e,t+1})\cdot\left(E^A_{e,h,t}/W_{h,t}\right) \quad \text{for each } (e,h,t) \tag{7}$$

$$\left(E^U_{e,h,t+1}/W_{h,t+1}\right) = (1-apei_{e,t+1})\cdot\left(E^U_{e,h,t}/W_{h,t}\right) \quad \text{for each } (e,h,t) \tag{8}$$

Consumers

Utility functions:

$$W_{h,t} = CES(C_{1,h,t},...,C_{J,h,t}, ES_{1,h,t},..., ES_{E,h,t}; \sigma^1_h,...,\sigma^V_h) \quad \text{for each } (h,t) \tag{9}$$

$$U_h = CES(W_{h,1},...,W_{h,T}; \sigma^{Util}_h) \quad \text{for each } h \tag{10}$$

Income balances – expenditures side:

$$p^W_{h,t}\cdot W_{h,t} = \sum_{j=1}^{J}(1+\tau_{j,h}\cdot\alpha_t)\cdot p_{j,t}\cdot C_{j,h,t} + p_{A,t}\cdot A_{e,h,t} + \sum_{e=1}^{E} p_{e,t}\cdot E_{e,h,t} \quad \text{for each } (h,t) \tag{11}$$

---

[10] As usual, '…' is used to indicate all items within the range as given by the items listed before and after.

A general nested CES production function with for example 4 inputs and 2 levels can be written as:

$Y = (a_1X_1^{\rho} + a_2X_2^{\rho} + a_{34}X_{34}^{\rho})^{1/\rho}$, and $X_{34} = (a_3X_3^{\psi} + a_4X_4^{\psi})^{1/\psi}$ for some parameters a_1, a_2, a_{34}, a_3, a_4, where $\rho=(\sigma-1)/\sigma$ and $\psi=(\varphi-1)/\varphi$. A convenient notation is: $Y = \mathrm{CES}(X_1, X_2, X_{34}; \sigma)$; $X_{34} = \mathrm{CES}(X_3, X_4; \varphi)$.

Income balances – income side:

$$\sum_{t=1}^{T} p_{h,t}^{W} \cdot W_{h,t} + p_{K,T} \cdot K_{h,T} = (1-\tau_{L,h}\cdot\alpha_t)\cdot p_{K,1}\cdot\frac{\overline{K_{h,1}}}{(r+\delta)} + \sum_{t=1}^{T}(1-\tau_{L,h}\cdot\alpha_t)\cdot p_{L,t}\cdot\overline{L_{h,t}} + \sum_{t=1}^{T}\sum_{e=1}^{E} p_{e,t}\cdot\overline{E_{e,h,t}} - \sum_{t=1}^{T}\tau_h^{LS}\cdot\alpha_t^{LS} + \sum_{t=1}^{T} TaxRev_{h,t} \quad \text{for each } h \tag{12}$$

Capital accumulation (as the volume of capital is free, the equation is written for the associated prices):

$$p_{K,t} = (1-\delta_K)\, p_{K,t+1} + r_{K,t} \quad \text{for each } t \tag{13}$$

Terminal condition on capital (transversality condition):

$$\sum_{h=1}^{H} K_{h,T} = (1+g_L)\cdot\sum_{h=1}^{H} K_{h,T-1} \tag{14}$$

Demographic developments:

$$\overline{L_{h,t+1}} = \overline{L_{h,t}}\cdot(1+g_L) \quad \text{for each } (h,t) \tag{15}$$

Rule for development in government expenditures:

$$\frac{W_{'government',t}}{W_{'government',0}} = \frac{\sum_{h=1,\, h\neq 'gov.'}^{H} W_{'privatehouseholds',t}}{\sum_{h=1,\, h\neq 'gov.'}^{H} W_{'privatehouseholds',0}} \quad \text{determines } \alpha_t \text{ and } \alpha_t^{LS} \tag{16}$$

Market clearance

Goods markets balance:

$$Y_{j,t} = \sum_{jj=1}^{J} Y_{j,jj,t}^{ID} + Y_{j,A,t}^{ID} + I_{j,t} + \sum_{h=1}^{H} C_{j,h,t} \quad \text{for each } (j,t)\text{; determines } p_{j,t} \tag{17}$$

Capital markets balance:

$$\sum_{j=1}^{J} K_{j,t} + K_{A,t} = \sum_{h=1}^{H}\overline{K_{h,t}} \quad \text{for each } t\text{; determines } r_{K,t} \tag{18}$$

Labour markets balance:

$$\sum_{j=1}^{J} L_{j,t} + L_{A,t} = \sum_{h=1}^{H}\overline{L_{h,t}} \quad \text{for each } t\text{; determines } p_{L,t} \tag{19}$$

Pollution permits markets balance:

$$\sum_{j=1}^{J} E_{e,j,t}^{U} + \sum_{j=1}^{J} E_{e,j,t}^{A} + E_{e,A,t}^{U} + E_{e,A,t}^{A} + \sum_{h=1}^{H} E_{e,h,t}^{U} + \sum_{h=1}^{H} E_{e,h,t}^{A} = \sum_{h=1}^{H}\overline{E_{e,h,t}} \quad \text{for each } (e,t) \tag{20}$$

determines $p_{e,t}$.

Savings/investments balance:

$$\sum_{h=1}^{H} S_{h,t} = \sum_{j=1}^{J} p_{j,t} \cdot I_{j,t} \quad \text{for each } t \tag{21}$$

Indices

Label	Entries	Description
j and jj	1,…,J,A	Production sectors, including Abatement sector (A) j={Agriculture, Industry, Services, Abatement sector}
h	1,…,H	Consumer groups h={Private households, Government}
e	1,…,E	Environmental themes e={Climate change, Acidification}
v_J	1,…,V_J	‘CES-knots’ in production functions v_J={Economic inputs, Environmental inputs, Production}
v_H	1,…,V_H	‘CES-knots’ in utility functions v_H={Goods, Environmental inputs, Consumption}
t	1,…,T	Time periods t={1998,1999,…,2030}

Parameters

Symbol	Description
g_L	Exogenous growth rate of labour supply
$apei_{e,t}$	Autonomous pollution efficiency improvement; assumed equal across all agents
δ_K	Depreciation rate
r	Steady-state interest rate
I^S	Base level investments (calibrated to steady-state)
K^S	Base level capital stock (calibrated to steady-state)
$\overline{L_{h,t}}$	Exogenous labour supply by consumer h in period t
$\overline{E_{e,h,t}}$	Endowments of pollution permits for environmental theme e by consumer h in period t
ι_j	Input share of good j for investments (by origin)
$\tau_{K,j}$	Tax rate on capital demand by sector j
$\tau_{L,j}$	Tax rate on labour demand by sector j

Symbol	Description
$\tau_{jj,j}$	Tax rate on input of good *jj* by sector *j*
$\tau_{j,h}$	Tax rate on consumption of good *j* by consumer *h*
$\tau_{K,h}$	Tax rate on the supply of capital by consumer *h*
$\tau_{L,h}$	Tax rate on the supply of labour by consumer *h*
τ_h^{LS}	Lumpsum transfer from government to consumer *h*, with $\sum_{h=1}^{H} \tau_h^{LS} = 0$ and $\sum_{h=1}^{H} \tau_h^{LS} \cdot \alpha_t^{LS} = 0$
τ^{SUB}	Lumpsum transfer from (excess) private households to the subsistence consumer
σ_j^v	Substitution elasticities between inputs combined in knot v_J in production function for sector *j*
$\sigma_{e,j}^A$	Substitution elasticities between pollution and abatement for environmental theme *e* in production function for sector *j*
σ_h^v	Substitution elasticities between consumption goods combined in knot v_H in utility function for consumer *h* (within same time period)
$\sigma_{e,h}^A$	Substitution elasticities between pollution and abatement for environmental theme *e* in utility function for consumer *h*
σ_h^{Util}	Intertemporal substitution elasticities in utility function for consumer *h* (between time periods)

Variables

Symbol	Description
$Y_{j,t}$	Production quantity of sector *j* in period *t*
$Y_{jj,j,t}^{ID}$	Demand for input *jj* by sector *j* in period *t*
$L_{j,t}$	Labour demand by sector *j* in period *t*
$K_{j,t}$	Capital demand by sector *j* in period *t*
$I_{j,t}$	Investment originating in sector *j* in period *t*
$I_{h,t}$	Investment by consumer *h* in period *t*
$\Pi_{j,t}$	(Net) profits in sector *j* in period *t* (equal to zero)
$E_{e,j,t}^U$	'Unabatable' emissions of environmental theme *e* by sector *j* in period *t*
$E_{e,j,t}^A$	'Abatable' emissions of environmental theme *e* by sector *j* in period *t*

Symbol	Description
$A_{e,j,t}$	Expenditures on abatement of environmental theme *e* by sector *j* in period *t* {note that $\sum_{e=1}^{E} A_{e,j,t} \equiv Y_{A,j,t}^{ID}$ }
$ES_{e,j,t}$	Emission services of environmental theme *e* by sector *j* in period *t*
$E_{e,h,t}^{U}$	'Unabatable' emissions of environmental theme *e* by consumer *h* in period *t*
$E_{e,h,t}^{A}$	'Abatable' emissions of environmental theme *e* by consumer *h* in period *t*
$A_{e,h,t}$	Expenditures on abatement of environmental theme *e* by consumer *h* in period *t* {note that $\sum_{e=1}^{E} A_{e,h,t} \equiv C_{A,h,t}$ }
$ES_{e,h,t}$	Emission services of environmental theme *e* by consumer *h* in period *t*
$W_{h,t}$	Welfare level of consumer *h* in period *t*
U_h	Total welfare of consumer *h* over all periods
$C_{j,h,t}$	Consumption of good *j* by consumer *h* in period *t*
$S_{h,t}$	Savings by consumer *h* in period *t*
$\overline{K_{h,t}}$	Capital supply by consumer *h* in period *t* (in 'flow' terms: capital services)
$p_{j,t}$	Equilibrium market price of good *j* (including A) in period *t*
$r_{K,t}$	Equilibrium market rental price of capital in period *t*
$p_{L,t}$	Equilibrium market wage rate in period *t*
$p_{e,t}$	Equilibrium market price of pollution permits for environmental theme *e* in period *t*
$p_{h,t}^{W}$	Equilibrium price of the 'utility good' (consumption bundle)
α_t	Endogenous change in existing tax rates to offset government income from sale of pollution permits in period *t*
α_t^{LS}	Endogenous change in lumpsum transfers to offset government income from sale of pollution permits in period *t*
$Taxrev_{h,t}$	Endogenous tax revenues for consumer *h* in period *t* (only nonzero for Government)

A1.2. Abatement as a durable good

The index *j*, which included the abatement sector in the non-durable case above, is limited in the durable-goods case to the non-abatement producers: *j={Agriculture, Industry, Services}*

The abatement specification is replaced by the following equations.

Base period abatement stock:

$$KA_{e,0} = \left(\sum_{j=1}^{J} AS_{e,j,0} + \sum_{h=1}^{H} AS_{e,h,0} \right) / (r_A + \delta_A) \tag{22}$$

Abatement investments[11]:

$$IA_t = CES(Y^{ID}_{1,A,t}, ..., Y^{ID}_{J,A,t}, K_{A,t}, L_{A,t}; \sigma^1_A, ..., \sigma^V_A) \quad \text{for each } t \tag{23}$$

Abatement accumulation:

$$KA_{e,t+1} = KA_{e,t} \cdot (1 - \delta_A) + \xi_e \cdot IA_t \tag{24}$$

Abatement services:

$$AS_{e,j,t} = \psi_j KA_{e,t} \cdot (r_A + \delta_A)\,. \tag{25}$$

$$AS_{e,h,t} = \psi_h KA_{e,t} \cdot (r_A + \delta_A)\,. \tag{26}$$

Transversality condition:

$$KA_{e,tlast} = (1 + g) \cdot KA_{e,tlast-1} \tag{27}$$

The equations for environmental services are adapted:

$$ES_{e,j,t} = CES(E^U_{e,j,t}, CES(E^A_{e,j,t}, AS_{e,j,t}; \sigma^A_{e,j}); \sigma^{ES}_{e,j}) \tag{3'}$$

$$ES_{e,h,t} = CES(E^U_{e,h,t}, CES(E^A_{e,h,t}, AS_{e,h,t}; \sigma^A_{e,h}); \sigma^{ES}_{e,h}) \tag{4'}$$

Goods production functions remain unchanged:

$$Y_{j,t} = CES(Y^{ID}_{1,j,t}, ..., Y^{ID}_{J,j,t}, K_{j,t}, L_{j,t}, ES_{1,j,t}, ..., ES_{E,j,t}; \sigma^1_j, ..., \sigma^V_j) \tag{1}$$

Utility functions remain unchanged:

$$W_{h,t} = CES(C_{1,h,t}, ..., C_{J,h,t}, ES_{1,h,t}, ..., ES_{E,h,t}; \sigma^1_h, ..., \sigma^V_h) \quad \text{for each } (h,t) \tag{9}$$

The market balance equations are adapted to represent the demand for goods by abatement investments in stead of by the abatement sector (but as the same symbols are used, the equation looks identical), and balance equations are added for abatement services and investment. Furthermore, the zero profit and income conditions are changed to reflect the differences in the build-up of environmental services (they now contain abatement services in stead of abatement expenditures).

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[11] Note that KA, the abatement stock, is not to be confused with K_A, the capital demand for abatement.

Parameters

Symbol	Description
δ_A	Depreciation rate of the abatement stock
r_A	Opportunity costs of abatement capital (in practice the steady-state interest rate)

Variables

Symbol	Description
ξ_e	Share of environmental theme *e* in the division of abatement investments (endogenous in the model)
ψ_j	Share of sector *j* in the services delivered by the abatement stock (endogenous in the model)
ψ_h	Share of consumer *h* in the services delivered by the abatement stock (endogenous in the model)
$AS_{e,j,t}$	Abatement services for environmental theme *e* by sector *j* in period *t*
$AS_{e,h,t}$	Abatement services for environmental theme *e* by consumer *h* in period *t*

A1.3. A simplified vintage specification of abatement

Production function (simplified notation, see above):

$$Y_{j,t} = CES(Y^{ID}_{i,j,t}, (ES^{N}_{e,j,t} + ES^{O}_{e,j,t}), K_{j,t}, L_{j,t}; \sigma_j) \qquad (1'')$$

New environmental services (simplified notation for pollution):

$$ES^{N}_{e,j,t} = CES(E_{e,j,t}, \varphi^{N}_{e,j,t} \cdot AS_{e,j,t}; \sigma^{AN}_{e,j}) \qquad (28)$$

where $\varphi_{e,j,t}$ gives the (normalised) state of technology ($\varphi_{e,j,tfirst} = 1$).

Extant environmental services:

$$ES^{O}_{e,j,t} = CES(E_{e,j,t}, \varphi^{O}_{e,j,t} \cdot AS_{e,j,t}; \sigma^{AO}_{e,j}) \qquad (29)$$

Survival of environmental services:

$$ES^{O}_{e,j,t+1} = (1-\delta_A) \cdot (ES^{O}_{e,j,t} + ES^{N}_{e,j,t}) \qquad (30)$$

Transversality condition

$$ES^{N}_{e,j,tlast} = (1+g) \cdot ES^{N}_{e,j,tlast-1}, \text{ or equivalently } ES^{N}_{e,j,tlast} = (g+\delta) \cdot ES_{e,j,tlast-1} \qquad (31)$$

For consumers, a similar set of equations are derived, where index *j* is replaced by index *h*:

$$W_{h,t} = CES(C_{i,h,t}, (ES^{N}_{e,h,t} + ES^{O}_{e,h,t}); \sigma_h) \qquad (9'')$$

$$ES^{N}_{e,h,t} = CES(E_{e,h,t}, \varphi^{N}_{e,h,t} \cdot AS_{e,h,t}; \sigma^{AN}_{e,h}) \qquad (32)$$

$$ES^{O}_{e,h,t} = CES(E_{e,h,t}, \varphi^{O}_{e,h,t} \cdot AS_{e,h,t}; \sigma^{AO}_{e,h}) \qquad (33)$$

$$ES^{O}_{e,h,t+1} = (1-\delta) \cdot (ES^{O}_{e,h,t} + ES^{N}_{e,h,t}) \qquad (34)$$

$$ES^{N}_{e,h,tlast} = (1+g) \cdot ES^{N}_{e,h,tlast-1}, \text{ or equivalently } ES^{N}_{e,h,tlast} = (g+\delta) \cdot ES_{e,h,tlast-1} \qquad (35)$$

Parameters

Symbol	Description
$\varphi_{e,j,t}$	Normalised state of technology ($\varphi_{e,j,tfirst} = 1$) of abatement for environmental theme *e* for sector *j* in period *t*.
$\varphi_{e,h,t}$	Normalised state of technology ($\varphi_{e,h,tfirst} = 1$) of abatement for environmental theme *e* for consumer *h* in period *t*.
$\sigma^{AN}_{e,j}$	New vintage substitution elasticities between pollution abatement for environmental theme *e* in production function for sector *j*
$\sigma^{AN}_{e,h}$	New vintage substitution elasticities between pollution and abatement for environmental theme *e* in utility function for consumer *h*
$\sigma^{AO}_{e,j}$	Extant substitution elasticities between pollution and abatement for environmental theme *e* in production function for sector *j*

Symbol	Description
$\sigma^{AO}_{e,h}$	Extant substitution elasticities between pollution and abatement for environmental theme *e* in utility function for consumer *h*

Variables

Symbol	Description
$ES^{N}_{e,j,t}$	New vintage emission services of environmental theme *e* by sector *j* in period *t*
$ES^{O}_{e,j,t}$	Extant emission services of environmental theme *e* by sector *j* in period *t*
$ES^{N}_{e,h,t}$	New vintage emission services of environmental theme *e* by consumer *h* in period *t*
$ES^{O}_{e,h,t}$	Extant emission services of environmental theme *e* by consumer *h* in period *t*

APPENDIX A2. THE BASE PERIOD ACCOUNTING MATRIX

A2.1. Abatement as a non-durable good

Table SAM(*,*) Base accounting matrix

	Agri.	Indu.	Serv.	Abat.	Priv.hh.	Gov't	colsum
Agri.	100	-52	-1	0	-47	0	0
Indu.	-23	400	-62	-2	-313	0	0
Serv.	-10	-75	475	-1	-339	-50	0
Abat.	-1	-6	-4	12	-1	0	0
Labour	-16	-119	-226	-6	367	0	0
Capital	-44	-120	-133	-3	300	0	0
lab.tax	-3	-20	-40	0	0	63	0
cap.tax	-3	-8	-9	0	0	20	0
lumpsum	0	0	0	0	33	-33	0
rowsum	0	0	0	0	0	0	0

Table Y_DATA(*,J) Producer data

	Agri.	Indu.	Serv.	Abat.
Sub.elas	1	1	1	1
Climate	0.11	0.6	0.14	0
Acid	0.19	0.33	0.24	0

Table HH_DATA(*,H) Household data

	Priv.hh.	Gov't
Savings	1	0
Sub.elas	1	0
Timeelas	0.5	0.5
Climate	0.15	0
Acid	0.24	0

Table E_DATA(*,E) Environmental data

	Climate	Acid
Elas.	1.25	1.4

Note that the column in SAM for the consumers contains not just the consumption expenditures, but also the investments. Investments are calculated as $Invsh_j \cdot I_0$, where $I_0 = (g+\delta)\cdot K_0$, and multiplied by $Savsh_h$ for distribution over the consumers. Consumption expenditures can then be calculated as the residual of the total consumer's expenditures. Distinguishing the 'utility producers'[12] and investments in the SAM gives the following matrix:

[12] The identification of these 'utility producers', that convert consumption goods into 'utility units' is purely for practical reasons; it does not influence the reactions of the households nor the working of the rest of the model. Distinguishing these utility producers is useful in the specification of abatement as a stock variable.

```
Table SAM(*,*) Base accounting matrix
            Agri.   Indu.   Serv.   Abat.  W_Priv  W_Govt      I0   Priv.   Gov't  colsum
Agri.         100     -52      -1       0     -22       0     -25       0       0       0
Indu.         -23     400     -62      -2    -203       0    -110       0       0       0
Serv.         -10     -75     475      -1    -249     -50     -90       0       0       0
Abat.          -1      -6      -4      12      -1       0       0       0       0       0
W_Priv          0       0       0       0     475       0       0    -475       0       0
W_Govt          0       0       0       0       0      50       0       0     -50       0
Labour        -16    -119    -226      -6       0       0       0     367       0       0
Capital       -44    -120    -133      -3       0       0       0     300       0       0
lab.tax        -3     -20     -40       0       0       0       0       0      63       0
cap.tax        -3      -8      -9       0       0       0       0       0      20       0
lumpsum         0       0       0       0       0       0       0      33     -33       0
savings         0       0       0       0       0       0     225    -225       0       0
rowsum          0       0       0       0       0       0       0       0       0       0
```

A2.1. Abatement as a durable good

The base period abatement data from the non-durable goods specification can be interpreted as the demand for abatement services in the base period: $AS_{t=0,j} = YA_{t=0,j}$

The accounting matrix has to be adjusted to reflect the base period endowments of abatement stock by the consumers (this base abatement stock is necessary in order to have sufficient abatement services in the first period). Moreover, the base period abatement investments must be taken into account; in fact, like with capital, the investments are represented in the accounting matrix, not the stock itself. These are based on the column for abatement in the non-durable goods specification, though the size of abatement investments differs from the size of the abatement sector in the non-durable goods specification.

So if AS_0=12 (aggregated over the sectors), then KA_0=12/(0.05+0.07)=100 (again, aggregated over the sectors) and IA_0=100*(0.02+0.07)=9.

It is assumed that the same $Savsh_h$ is used for distribution of the abatement investments over the consumers.

The accounting matrix for this specification looks as follows:

```
Table SAM(*,*) Base accounting matrix
               Agri.   Indu.   Serv.  W_Priv  W_Govt      I0     IA0   Priv.   Gov't  colsum
Agri.            100     -52      -1     -22       0     -25       0       0       0       0
Indu.            -23     400     -62    -203       0    -110      -2       0       0       0
Serv.            -10     -75     475    -249     -50     -90      -1       0       0       0
W_Priv             0       0       0     475       0       0       0    -475       0       0
W_Govt             0       0       0       0      50       0       0       0     -50       0
AS                -1      -6      -4      -1       0       0       0      12       0       0
Labour           -16    -119    -225       0       0       0      -4     364       0       0
Capital          -44    -120    -134       0       0       0      -2     300       0       0
lab.tax           -3     -20     -40       0       0       0       0       0      63       0
cap.tax           -3      -8      -9       0       0       0       0       0      20       0
lumpsum            0       0       0       0       0       0       0      33     -33       0
savings            0       0       0       0       0     225       9    -234       0       0
rowsum             0       0       0       0       0       0       0       0       0       0
```

Compared to the previous (non-durable goods) specification, the changes are in the representation of abatement: the ‘abatement sector’ `(Abat.)` is no longer part of the matrix, as it are the abatement services and investments that have to be specified for the base period. Note that the changes in the abatement specification have to be match by (minor) changes in other entries in the table, especially by changes in the labour market.

A2.3. A simplified vintage specification of abatement

The simplified vintage specification does not require any changes to the base period data.