DYNAMICS IN AN APPLIED GENERAL EQUILIBRIUM MODEL WITH POLLUTION AND ABATEMENT

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ABSTRACT

This article presents a dynamic AGEM with pollution and abatement. Polluters have the choice between paying for pollution rights or investing in abatement. A CES function is calibrated to fit the marginal abatement cost curves, and thus describes the sector- and environmental theme-specific possibilities to substitute between pollution and abatement. Hence, the advantages of the AGE approach are combined with information on abatement techniques. The AGE model is kept simple, to allow maximum focus on dynamic interactions between economy and environment. The numerical results show that the specification of the dynamics is relevant for both the transition and equilibrium paths.

Keywords: applied general equilibrium, dynamics, pollution abatement

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[1] For the latest version of this paper and related material visit the website http://www.sls.wau.nl/me/staff/dellink/dellink.html.

1 INTRODUCTION

This article presents a dynamic applied general equilibrium (AGE) model with pollution and abatement for the Netherlands. The model is part of a larger research project, which aims at enhancing the understanding of the dynamic feedback mechanisms between economic variables and abatement in the context of environmental policy. An augmented version of the model will be used in empirical analysis of the impacts of environmental policy on economic growth, welfare and the adoption of abatement techniques. A full empirical analysis is beyond the scope of the current paper.

The main objective of this article is to develop a methodology to integrate the bottom-up information on technical measures to reduce pollution (the characteristics of the abatement techniques) into a top-down multi-sectoral applied general equilibrium framework. To this end, a dynamic applied general equilibrium model is constructed including pollution and abatement. The dynamic setting is essential, as most of the major interactions between the economy and the environment are essentially dynamic in nature and capital formation is a typically dynamic phenomenon. Different ways in which the dynamic issues may be specified are analysed in the model.

Standard AGE models do not pay explicit attention to the characteristics of the technologies involved, but use smooth, continuous production and utility functions. 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 precludes the use of discrete technology modelling in broad empirical environmental-economic analysis. Therefore, in this article a new methodology is introduced[2] in which the advantages of the top-down approach are combined with the main information of the bottom-up approach.

This study concentrates on the economic consequences of pollution and abatement, while environmental stocks and damages by poor environmental quality on the economic system or on welfare are not taken into account. The environmental sub-model is purely represented by the pollution levels and abatement activities.

In Section 2, different approaches to a dynamic specification of the AGE model are presented and compared. Section 3 presents a general overview of the main economic and environmental modelling issues. Then, in Section 4, a numerical example shortly illustrates the working of the model. Section 5 contains the conclusions.

2 DIFFERENT APPROACHES TO DYNAMIC AGE MODELS

Three proto-type AGE models are presented, each reflecting a different approach to the dynamic issues: a steady-state model, a recursive-dynamic model and a forward-looking model.

2.1 Empirical AGE studies with environmental issues

In this section, a short discussion of the most relevant literature is presented; a broader and more detailed survey of the relevant literature is given in separate paper.

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[2] Essentially the same methodology is used in a static framework in Verbruggen (1999).

Most AGE models that include environmental issues adopt a static framework. Two (well-known) authors that have persistently analysed environmental issues using static AGE models are Bergman (see for example Bergman, 1991) and Conrad (see for example Conrad and Schroeder, 1993). These models focus on national economies. For the Dutch economy, static AGE models with environmental issues include HERMES (SEO, 19xx) and Dellink and Jansen (1997). Recent additions to the international literature include Naqvi, 1998, and Parry and Williams, 1999.

Looking at global AGE models with environmental issues, the three most well-known models are without doubt OECD's GREEN model (see Lee *et al.*, 1994), the MERGE model by Manne and Richels (Manne and Richels, 1999) and the DICE model by Nordhaus (Nordhaus, 1994).

Dynamic AGE models that include environmental issues are not very common. While the literature on dynamic AGE models is expanding (*e.g.* Devarajan and Go, 1998), dynamic AGE models that focus on the environment are rather limited. Jorgenson has carried out several dynamic analyses of environmental policy questions within an AGE context (see for example Jorgenson and Wilcoxen, 1993). He uses econometric estimation of the relevant parameters, based on long-term US economic data. Other studies using dynamic AGE models with environmental issues include Böhringer, 1998 and Böhringer *et al.*, 1999.

2.2 Different types of dynamic modelling

The simplest dynamic AGE model is a steady-state model. Essentially, a steady-state model is a static model (there is only one period), where some steady-state conditions are satisfied (primarily with respect to investments). The steady-state model is useful to illustrate the balanced growth path that may emerge in the long run and can be used to analyse the steady-state properties of the equilibrium. This type of model can however not be used to analyse the transition paths from the current growth path to a sustainable growth path.

The second type of model explored in this paper is the recursive-dynamic AGE model. This type of dynamic model is characterised as a series of individual one-period model simulations, and is based on the assumption that agents in the economy have no forward-looking behaviour. Hence, the model can be solved recursively, for each period separately, where the periods are linked through the capital stock. In comparison to the steady-state model, the recursive-dynamic approach has some major advantages: it enables the calculation of the transition path from the initial steady-state to a new steady-state, which is of particular importance for policy making, and which cannot be studied in a steady-state model. Naturally, the inclusion of the transition path may have significant impacts on any policy recommendations to be drawn from the analysis.

The third type of dynamic AGE model investigated here is the forward-looking model, like the standard Ramsey model with perfect foresight and certainty. This type 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 (see 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 (see Solow, 1974). Consequently, the forward-looking and recursive-dynamic models provide extreme cases between which decision making in reality resides.

An alternative specification of the forward-looking model could be to assume that consumers maximise their discounted utility based on current prices and expectations of the future (and reconsider their actions in the next period when expectations change). This can be done in a temporary equilibrium framework or using the theory on incomplete markets. These models are closer to reality in this respect, but it may be hard to find good expectations functions for future prices and profits.

All model types discussed above are based on a finite number of periods approximation of the infinite-horizon assumption. A model is set-up for T periods, and all periods after that horizon are irrelevant to the model (apart from some transversality conditions concerning capital stock and utility after the last period). Consequently, the total number of markets (both current and future) and thus the number of decision variables is finite. Alternatively, one could specify an infinite-horizon model; these include two sub-types: Overlapping Generations (OLG) models and dynastic models. In the OLG models, consumers live for a finite time (longer than one period but shorter than the model horizon), so that in each period, two or more generations co-exist; the number of generations is infinite. The OLG framework thus deviates from the dynastic model, which assumes a finite number of consumers that live infinitively long and a social planner that ensures an optimal solution (see Ginsburgh and Keyzer, 1997). A recent example of an environmental-economic OLG-model is Gerlagh, 1999.

3 A PROTO-TYPE AGE MODEL WITH POLLUTION AND ABATEMENT

This section discusses the basic assumptions that are needed to build a multi-sectoral (dynamic) applied general equilibrium (AGE) model, including a specification of environmental pollution and abatement activities[3].

3.1 Modelling economic issues

The model is of the *applied general equilibrium* (AGE) type. A general equilibrium model consists of a set of ‘economic agents’ (like consumers and producers), each of which demands and supplies commodities or services (hereafter denoted in brief as ‘goods’). Agents are assumed to behave rationally. Each agent solves its own optimisation problem. The agents take prices, which give information about the decision environment (like the behaviour of other agents and government policies), as given. Equilibrium is defined as a state of the economy in which the actions of all agents are mutually consistent and can be executed simultaneously. In other words, demand must equal supply on all markets and equilibrium is attained by adjusting relative prices. See Shoven and Whalley, 1992 or Ginsburgh and Keyzer, 1997 for more details.

Generally, there are two categories of agents: consumers and producers. 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 production technology, for given prices. Demand and supply, which result from the agents’ optimisation problems, meet each other on the markets. The model is written in GAMS in what Ginsburgh and Keyzer (1997) call a ‘CGE format’, which means that the model is formulated as a system of non-linear equations that can be solved simultaneously. This format implies that no Negishi weights have to be constructed for the various consumer groups.

In the current model version of the model, there is no international trade. This allows for an endogenous interest rate in the various model types.

[3] A detailed description of the model specifications used in this article is available from the author on request.

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). 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.

For government behaviour 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.

In the steady-state and recursive-dynamic model, the households optimise current utility subject to the (current) budget constraint. Intertemporal borrowing of funds is not possible in these two models. In the forward-looking model, the 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 for each individual period, so that intertemporal borrowing of funds is assumed possible.

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. In the steady-state model there is no increase in labour supply (as there are no periods distinguished).

The (total) capital stock is determined endogenously within the model; the way in which capital and investments are specified differs between the model types. In the steady-state model, the capital stock is determined by the steady-state requirements, where the (new equilibrium) rental price of capital is constrained so that the price of new capital equals the price of existing capital (*i.e.* the value of Tobin's Q equals unity; see Hayashi, 1982). These conditions also determine the optimal savings and investment level in the steady-state model.

In the recursive-dynamic model, the total capital stock and investment level is determined for each period after solving the model for that period, using a constant proportion of household income for savings (and the savings level determines total investments). Then, using the new investment level and capital stock, the model is solved for the next period. The recursive-dynamic specification is hence essentially a model in the Solow-Swan tradition.

In the forward-looking model, 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.

The share of both produced goods in investments are fixed exogenously in all models. Consumer savings reduce consumption so that the consumer income condition holds.

The nested-CES production function consists of the input of labour and capital and intermediate deliveries from the other producing sector. 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. These are discussed separately below.

3.2 Modelling environmental issues

Production processes lead to pollution. This pollution is regarded as a necessary input for the production functions (though it seems more natural to view pollution as ‘unwanted output’, it can equivalently be regarded as a necessary input in the production of economic outputs; the key is that there is correspondence between production and pollution for a given technology). In the policy scenarios, this pollution is controlled by the government by means of tradable environmental ‘pollution permits’, that the producers (and consumers) can buy from the government (the proceeds are used to reduce existing taxes). 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. By consuming, the households also inevitably pollute. Just as the producers, the households can either pay for pollution permits or invest in abatement[4]. Environmental quality is not directly included in the utility function, but consumers’ environmental expenditures do have an impact on the maximum consumption and utility level achievable.

A third possibility for producers (consumers) is of course to reduce 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). At low levels of required pollution reduction, this is not likely to be a viable option. However, if the required pollution reduction is set at a much more ambitious level, which may not be unrealistic when striving for (strong) sustainability, then both the costs of buying the pollution permits and the costs of investing in further abatement may become extremely high and reducing production (consumption) may become a least-cost strategy[5].

Normal AGE models describe the technical possibilities to change the production (or consumption) structure in the form of smooth elasticities of substitution, without paying explicit attention to the characteristics of the technologies involved. 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). In principle, both approaches can be reconciled: the available techniques can be explicitly modelled in a general equilibrium framework so that both the technical information and the indirect effect are taken into account (see Böhringer, 1998, where the same complementarity format is used as here).

However, practical problems stand in the way of using this integrated approach: when one looks at several environmental themes and wants to include information on all available technologies, the number of techniques that have to be specified gets very large (for climate change alone, there are around a thousand abatement techniques available; see De Boer, 1999 and Dellink and Van der Woerd, 1997). This precludes the use of discrete technology model-

[4] 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.

[5] Note that from a macro-economic point of view the labour that is ‘freed’ when reducing production in one sector may be used in a profitable way in other (less polluting) production sectors, if these have less pollution associated or have lower abatement cost options available.

ling in broad empirical environmental-economic analysis. Therefore, in this article a new methodology is introduced in which the advantages of the top-down approach are combined with the main information of the bottom-up approach. To this end, the bottom-up information is aggregated into so-called abatement cost curves, which give the marginal abatement costs for increasing levels of pollution reduction. These abatement cost curves also provide the information on the total (technical) potential of pollution reduction. Then, these abatement cost curves are approximated by means of an 'iso-output curve' that reflects the trade-off between pollution and abatement. These iso-output curves are then implemented in the AGE model.

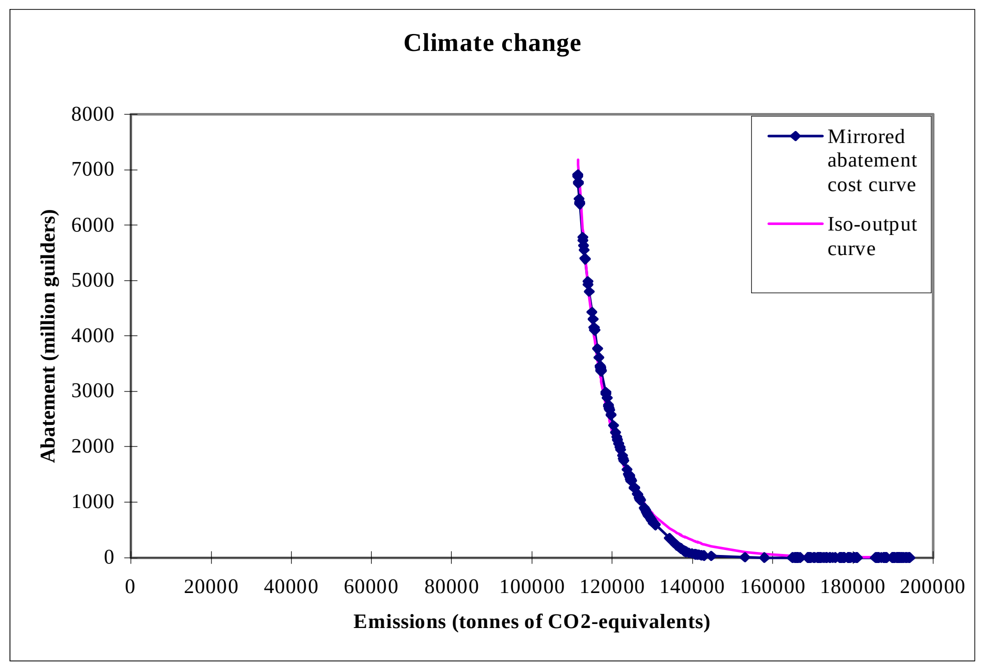
The abatement process is modelled as a separate producer, where 'abatement goods' are produced using both produced goods and primary production factors as inputs. This is roughly in line with Nestor and Pasurka (1995), but there the abatement producer is an implicit part of the government sector, and hence does not have a specific structure. In our model, a CES production function is calibrated, for which the data are derived from abatement cost curves: these inputs 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. As a result, one abatement producer suffices to represent the abatement possibilities.

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

As the abatement cost curves are translated for each producer and environmental theme into an 'iso-output curve' of pollution and abatement, the abatement possibilities are presented as a function of pollution and not as a function of pollution reduction. Then, a CES function is calibrated to best fit the iso-output curve and the CES-elasticity thus estimated describes the sector-specific, environmental theme-specific possibilities to substitute between pollution and abatement.

Figure 1 illustrates the concept of the abatement cost curve and iso-output curves. Note that the figure differs from a normal representation of abatement cost curves in that the x-axis gives pollution instead of pollution reduction. In the case of climate change, emissions in the Netherlands can be reduced from 195 kilotonnes of CO_2-equivalents to a little above 110 kilotonnes CO_2-equivalents. Each mark on the line with markers gives an individual technical measure; the line without markers gives the estimated iso-output curve. The average quadratic deviation between a technical measure and the estimated figure is 0.04%. This indicates that the iso-output curve represents the technical options very well. Naturally, for other environmental themes this fit may be less perfect if the number of technical measures is lower.

Figure 1. An iso-output curve for climate change



Though this approach may not seem very flexible at first glance, preliminary empirical analysis suggests that for all environmental themes the abatement cost curves can be fitted with a difference of less than one and a half percent margin of error (see Verbruggen, 1999). Hence, the approach taken here is relatively easy and straightforward, but a still rather accurate methodology to integrate the (bottom-up) technical measures into the (top-down) AGE model. 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).

Environmental policy is implemented by determining the number of pollution permits the government auctions: in the base simulations, the government distributes exactly the number of permits that allows the producers and consumers to maintain their original behaviour. The price of the permits is endogenously determined on the market by equating demand and supply, just like other prices. The revenues from the sale of the permits to producers and consumers is – by assumption – used by the government to reduce existing taxes proportionately. If the government wishes to reduce total pollution by x percent, it just takes away x percent of the permits.

A direct effect of a reduction in the number of permits is, *ceteris paribus*, a reduction in the government revenues from the permits. This puts an upward pressure on other taxes. However, as always, the AGE model is full of (mitigating) indirect effects: the producers and consumers will change their behaviour, shift towards more environmentally-friendly techniques, and invest in abatement. Moreover, as the supply of permits decreases, the price of the permits will increase; this will also mitigate the loss in government revenues. On balance, the government revenues may go up or down, depending on the value of the price elasticities of demand for pollution permits by the producers and consumers.

Although the analysis of the optimal timing of policies is not a direct aim of this study, the framework is highly suited to investigate the consequences of speeding up or deferring environmental policy targets. At this stage, annual environmental targets will be satisfied and the development of these targets over time is assumed exogenous.

4 A NUMERICAL EXAMPLE

The three models presented here are highly stylised. They may be called ‘proto-type models’, as they are used only to highlight the methodology presented above. For good empirical assessments of environmental policies, these proto-type models have to be augmented in several ways. These empirical issues will, however, not influence the main methodology presented in this article.

The proto-type models described above are illustrated with a numerical example. The main goal of this section is to show the main mechanisms that are at work in the model and how these mechanisms are influenced by the basic modelling assumptions.

4.1 Parameter values for the numerical example

All three proto-type models start from the same accounting matrix that describes the initial equilibrium. This accounting matrix is represented in table 1 below.

Table 1. Initial accounting matrix

	Y1	Y2	Abat.	priv	govt	colsum	price
Y1	100	- 10	- 5	- 73	- 12	0	1
Y2	- 10	100	0	- 80	- 10	0	1
Abat.	- 5	- 5	15	- 5	0	0	1
l	- 40	- 25	- 3	68	0	0	1
k	- 25	- 40	- 5	70	0	0	1
taxl	- 15	- 10	- 1	0	26	0	1
taxk	- 5	- 10	- 1	0	16	0	1
taxls	0	0	0	20	- 20	0	1
rowsum	0	0	0	0	0	0	

Note: ‘Y1’ and ‘Y2’ indicate the two producers; ‘Abat.’ indicates the abatement sector; ‘priv’ stands for the private households and ‘govt’ for the government consumer; ‘l’ and ‘k’ are the primary production factors labour and capital, respectively; ‘taxl’ are taxes on labour, ‘taxk’ are taxes on capital use and ‘taxls’ are lumpsum transfers between government and consumers; the ‘price’ column gives the prices associated with the rows; ‘rowsum’ is the sum over all rows within a single column and ‘colsum’ is the sum over all columns within a single row.

In the accounting matrix, production outputs and consumer endowments are given as positive values, inputs and consumption are given as negative values.

Table 2. Additional producer data

	Y1	Y2	Abat.	Explanation
InvSh	0.75	0.25	0.00	Share in origin of investments
Elas	1.0	1.0	1.0	Substitution elast. between inputs
Elas2	1.4	1.4	0.0	Subst. el. between pollution and abatement
CO_2	0.5	0.2	0.0	Share in total pollution of CO_2
NO_x	0.7	0.1	0.0	Share in total pollution of NO_x

Table 3. Additional consumer data

	Priv	Gov't	Explanation
SavSh	1.0	0.0	Share in total savings
Sigma	0.5	0.5	Intertemporal subst. el. (forsight-model)
Elas	1.0	0.0	Subst. el. between consumption goods
Elas2	1.4	0.0	Subst. el. between pollution and abatement
CO_2	0.3	0.0	Share of polluter in total pollution of CO_2
NO_x	0.2	0.0	Share of polluter in total pollution of NO_x

Additional producer and consumer data is given in Tables 2 and 3, respectively. The growth rate is induced by an annual 2 percent autonomous increase in labour supply (except in the steady-state model where there is no place for annual growth); the depreciation rate is set at 7 percent and the interest rate at 5 percent.

The base year for the model simulation is 1998. To allow a sufficiently long period for stabilisation to the steady-state, the model horizon is chosen at 2130; it is expected that any short-term deviations from the long-term growth paths will have faded out by then. The policy period is much shorter: 1998 till 2030. Environmental policy after the policy period (2030-2130) is assumed to be aimed at keeping total emissions constant at the level of 2030.

Sustainability is assumed to be achieved if annual pollution levels are decreased with 80 percent for both CO_2 and NO_x emissions.

4.2 The policy alternatives

The models as specified above are used for four alternative policy simulations. These alternatives are not based on actual environmental policy in the Netherlands, nor do they reflect empirical estimates of 'sustainable' paths of pollution. They are just a numerical example, chosen to give insight in the dynamic workings of the model specifications.

In the first simulation, the number of environmental permits is kept constant at the 1998 level until 2015, in 2015 the number of permits is reduced to a (fictitious) sustainable level and from 2015 to 2030 (and in all periods after that) kept constant at the sustainable level. This policy is labelled '1: *Shock-Sustainability*'.

In the second simulation (labelled '2: *Gradual-Sustainability*'), a linear reduction in the number of pollution permits is implemented, where the sustainable number of permits is reached in 2030 (and kept constant at this level until the model horizon). Comparison with the first simulation indicates the differences between the impact of a gradually implemented policy versus instant-shock.

In the third simulation, the number of permits is set at the sustainable level throughout the whole period 1998-2030 (and thereafter). It should be noted that the environmental consequences of this '*Immediate-Sustainability*' policy simulation differ: total pollution summed over all periods is lower than in the other simulations; this is especially important for stock-pollutants, where the concentrations of a pollutant matter and not just the annual pollution levels.

In the fourth simulation, the number of permits is kept constant throughout the model horizon at a level above the sustainable level, but below actual pollution levels of 1998 (this simulation is labelled '4: *Above-Sustainability*'). In this case, the allowed number of permits is set halfway between the actual and sustainable pollution level. Consequently, total pollution, summed over the policy period, is equal to total pollution in the policy-period in the first and second simulation.

So, summing up, the timing of environmental policies differs between the four simulations. In the first three simulations, long-term pollution is set at a sustainable level. In the first, second and fourth simulation, the total pollution, summed over the policy period, is equal.

All policy alternatives will be compared to the common baseline, which is kept as comparable as possible between the different model types. The baseline contains the simulation of the model using the data as described in Section 4.1, without new environmental policy. In the baseline it is assumed that the economy is in a steady-state in the first year of the simulations (1998), and would continue to move along the steady-state path if pollution levels could rise unrestrictedly. However, it is assumed that there is standing environmental policy, which means that pollution levels are kept constant at the level of 1998[6]. Consequently, the baseline cannot be characterised as a steady-state path.

4.3 The steady-state model

In the steady-state model, the timing of environmental policy cannot be modelled properly. Therefore, only simulations 3 and 4 will be investigated for this model type. The following table 4 compares the new steady-state equilibrium that arises under environmental policy to the original steady-state equilibrium.

In the *Immediate-Sustainability* simulation, Gross Domestic Product (GDP) decreases with 2.79% (see Table 4). This is in line with the common opinion that environmental policy will have at most moderate impacts on the economy. Note that GDP does not capture all welfare effects of the environmental policy (such as the amenity value of a clean environment). It would therefore be misleading to label the GDP result as ‘welfare change’.

In the *Above-Sustainability* simulation pollution control is less ambitious. Comparing both policies as shown in table 4 gives an impression of the non-linearity of the model. It is clear that the economic costs in terms of GDP are non-linear, at least for the (rather stringent) policy goals shown here: a doubling of environmental policy induces a decrease in equivalent variation almost three times as large.

Table 4. Changes in main variables (steady-state model)

(%-change of volumes)	3: *Immediate-Sustainability*	4: *Above-Sustainability*
Gross Domestic Product	-2.79%	-1.01%
Private consumption of Y1	-3.66%	-1.10%
Private consumption of Y2	-2.45%	-0.99%
Sectoral production Y1	-2.36%	-0.74%
Sectoral production Y2	-2.64%	-1.01%
Investments	-2.62%	-0.99%
Abatement expenditures	15.30%	5.44%
CO_2 emissions	-80%	-40%
NO_x emissions	-80%	-40%

[6] This baseline is calculated as a simulation with a system of tradable pollution permits where the number of permits equals the initial pollution levels. The implementation of a system of tradable permits may affect the allocation of resources, but *ceteris paribus* this effect is negligible: at maximum, in the recursive-dynamic model the effect will slowly increase over time to around 0.15% change in GDP. Note that as pollution is already controlled, there are positive abatement expenditures in the baseline.

The reduction in allowable pollution in the simulations does not have a symmetrical impact on both producers. Producer Y1, which is responsible for 50% of CO_2 emissions and 70% of NO_x emissions and is thus more polluting than producer Y2, is expected to incur the most costs. This is however not reflected in the production losses of both sectors: in both simulations sector Y2 is hurt more severely than sector Y1 (see table 4). This can largely be attributed to the increased demand for Y1-goods by the abatement sector (that does not demand Y2-goods at all): demand for Y1 by the abatement sector increases with 13.8% in the *Immediate-Sustainability* simulation and with 4.3% in the *Above-Sustainability* simulation (not reported in table 4).

Abatement expenditures are also not evenly spread across both sectors. Though in this proto-type model the marginal abatement cost curve is assumed to be identical for both producers, producer Y1 will invest more in abatement: abatement expenditures in the *Immediate-Sustainability* (*Above-Sustainability*) simulation increase with 29.7% (9.9%) percent for Y1 and with 5.5% (2.2%) percent for Y2 (not reported in table 4). In a sense, one could say that production sector Y1 can limit its own production losses by stimulating the abatement sector that demands a lot of Y1 goods. But the Y1 sector does not have much choice: given the high initial pollution levels of Y1, it will either have to buy a huge amount of pollution permits (and consequently pay a high price) or it will have to invest in abatement. Furthermore, even if Y1 would be able to buy all pollution permits, it would still have to reduce it's pollution levels, as initial pollution by sector Y1 is higher than the number of permits available (except for CO_2 in the *Above-Sustainability* simulation).

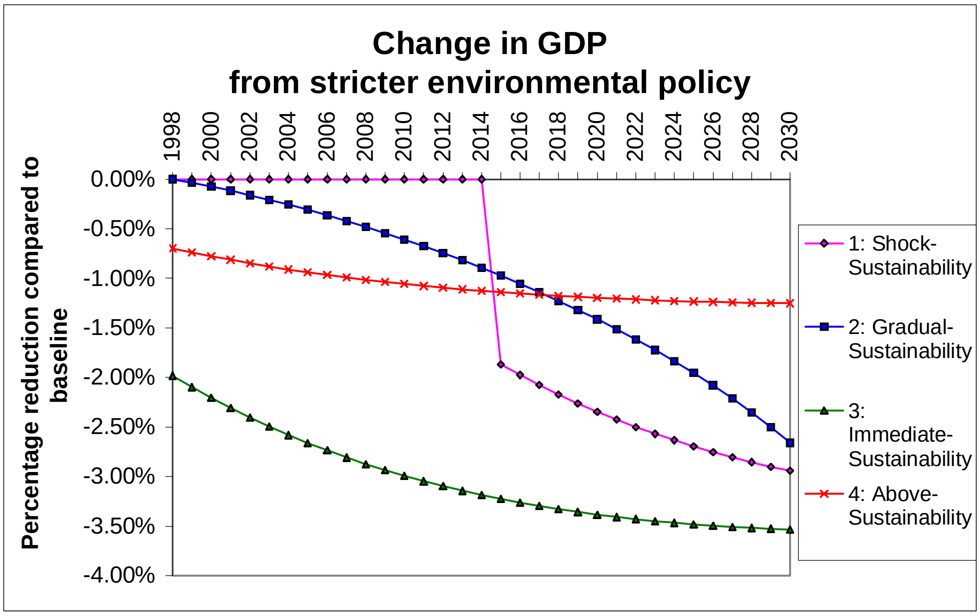
For the *Immediate-Sustainability* simulation, the investment level is in between the consumption reduction for goods Y1 and Y2, and roughly in line with the fall in equivalent variation. This indicates that the new steady-state that emerges will be characterised by somewhat lower growth levels than the base simulation: the resulting balanced growth path is less steep than the baseline balanced growth path. For the *Above-Sustainability* simulation, the investment level decreases with the same order of magnitude as the consumption levels. If environmental policy is more stringent, a larger decrease in consumption and economic growth has to be accepted, because the marginal cost of pollution reduction increases with the level of environmental policy.

Abatement expenditures are tripled if environmental policy is twice as stringent: as the number of pollution permits distributed by the government is reduced further, the price of the permits will increase, and it will become more cost-effective to invest in abatement. The marginal costs of abatement also increase with increasing investments in abatement and the final resulting equilibrium is characterised by the point where the marginal abatement costs equal the price of the pollution permits. In this (cost-effective) point, the producers are indifferent between investing in abatement and paying for the pollution permits.

4.4 The recursive-dynamic model

The recursive-dynamic proto-type model is used to calculate the effects of all four alternative environmental policies described in Section 4.2. Figure 2 presents the change in national product (GDP) of the policies over the policy period 1998-2030.

Figure 2. Results for four environmental policies – recursive-dynamic model



The differences in the timing of environmental policy clearly lead to analogous differences in the timing of the economic impacts: the 'shock-period' 2015 in the *Shock-Sustainability* simulation is reflected by a sudden drop in GDP. As there is no forward-looking behaviour by the agents, this was expected. The steadily decreasing GDP in the *Gradual-Sustainability* simulation is also in direct correspondence with the strictness of environmental policy.

The total number of permits issued in the period 1998-2030 is the same in three simulations (*Shock-Sustainability*, *Gradual-Sustainability* and *Above-Sustainability*). This is roughly reflected in the present value of the GDP losses in those simulations over that period: in the *Shock-Sustainability* simulation the present value GDP loss over the period 1998-2030 is –0.91% compared to the base, while in *Gradual-Sustainability* it is –0.84%; for *Above-Sustainability* the drop is –1.03% (not represented in figure 2).

The largest drop in GDP is clearly in the *Immediate-Sustainability* simulation. For each year within the policy period GDP is below the GDPs of the other simulations; the present value of the GDP loss over the period 1998-2030 is –2.92%. This is a direct consequence of the lower number of environmental permits available.

In table 5, the results are given for some main variables for the years 2030 (the end of the policy period) and 2130 (the planning horizon).

Table 5. Changes in main variables for 2030 and 2130 (recursive-dynamic model)

(%-change of volumes)	*Shock-Sustainability* 2030	*Shock-Sustainability* 2130	*Gradual-Sustainability* 2030	*Gradual-Sustainability* 2130	*Immediate-Sustainability* 2030	*Immediate-Sustainability* 2130	*Above-Sustainability* 2030	*Above-Sustainability* 2130
GDP	-2.94%	-2.49%	-2.66%	-2.50%	-3.53%	-2.44%	-1.25%	-0.88%
Priv. cons. of Y1	-2.78%	-2.29%	-2.56%	-2.29%	-3.25%	-2.26%	-1.15%	-0.81%
Priv. cons. of Y2	-2.50%	-2.34%	-2.17%	-2.34%	-3.21%	-2.29%	-1.14%	-0.83%
Production of Y1	-1.94%	-1.82%	-1.68%	-1.82%	-2.49%	-1.79%	-0.88%	-0.64%
Production of Y2	-2.56%	-2.37%	-2.24%	-2.37%	-3.26%	-2.32%	-1.16%	-0.84%
Investments	-3.74%	-2.88%	-3.48%	-2.88%	-4.25%	-2.79%	-1.51%	-1.01%
Abatement costs	12.30%	5.81%	12.66%	5.81%	11.54%	5.85%	4.15%	2.13%
CO_2 emissions	-80%	-80%	-80%	-80%	-80%	-80%	-40%	-40%
NO_x emissions	-80%	-80%	-80%	-80%	-80%	-80%	-40%	-40%

The values for GDP in 2030 correspond to the values in figure 2. By assumption, the number of pollution permits is kept constant after 2030. As labour productivity increases over time, abatement techniques become cheaper every period. Consequently, the drop in consumer's income from the environmental policy gets smaller over time. This is reflected in the GDP loss for 2130: for all simulations the decrease in (current value) GDP is smaller in 2130 than in 2030.

Though in the early periods consumption of Y1 decreases more than consumption of Y2 (as shown in the columns for 2030), this is no longer the case in the balanced growth path (as indicated by the columns for 2130).

Production of sector Y2 decreases more than that of sector Y1 in all simulations. The main reason for this is the increasing demand for Y1-goods by the abatement producer. This more than counteracts the downward pressure on production of Y1 due to the large pollution levels of that sector. Though this conclusion depends on the specific characteristics of the illustrative example, a general conclusion to be drawn may be that pollution-intensive sectors do not always have to be the most heavily impacted by environmental policy. Other factors can mitigate the negative direct impact of environmental policy on these sectors; these factors include the demand relations with the abatement production sector and the demand elasticities by the other production sectors and by consumers. Moreover, the existing tax burden plays a role. This is central to AGE models: indirect effects, that arise from the initial shift in relative prices will impact all model variables. AGE models include a large number of these mitigating effects that are ignored by other model types (like input-output models).

In the recursive-dynamic model, savings are a fixed proportion of household income. However, as the relative prices of the goods that make up investments change, the change in investments will not be equal to the average change in consumption.

As expected, abatement expenditures increase. The size of the increase is large, but not huge, especially considering the strictness of environmental policy. For 2030, the increase in abatement expenditures is somewhat over 10 percent, except in the *Above-Sustainability* simulation (see Table 5). For the larger part, these abatement expenditures are made by producer Y1, where the increase is almost 25%; in sector Y2, the increase is only around 3%. This is in spite of the fact that the available abatement measures are assumed identical for both sectors. As in the steady-state model, production sector Y1 does on the one hand have a large environmental costs (abatement expenditures and pollution permits), but on the other these abatement expenditures bring about a boom in the demand for goods of Y1, consequently mitigating the output losses of the sector.

Comparing the simulation results in table 5 it becomes clear that the timing of environmental policy does have some impact on the magnitude of the main model variables in the short run, but the qualitative results and long-run quantitative results are rather indifferent to the timing of the policy.

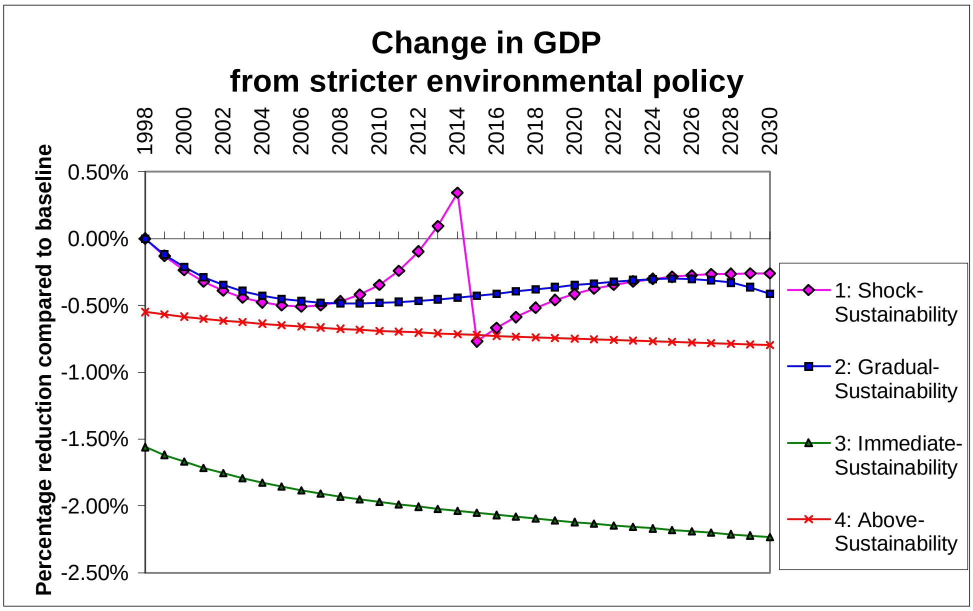
4.5 The forward-looking model

The last proto-type model that is constructed differs from the previous in that it assumes forward-looking behaviour of the consumers: households maximise the total present value of all current and future consumption. Consequently, the model is solved for all periods together and the growth path in the periods between the initial steady-state equilibrium and the new equilibrium is endogenously determined.

The same four simulations are carried out as in the recursive-dynamic model. It is expected that the forward-looking behaviour will lead to a more 'smoothed' development of economic growth and utility, as consumers anticipate on reductions in the number of pollution permits allowed in later periods. This is expected to be most striking in the first simulation (*Shock-Sustainability*).

Figure 3 shows the changes in Gross Domestic Product in the four simulations.

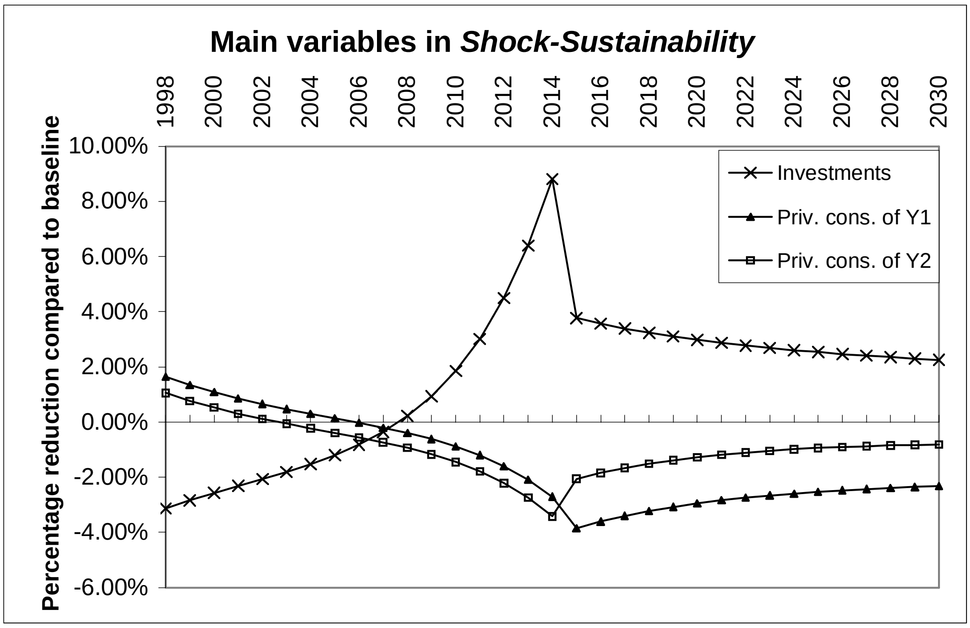
Figure 3. Results for four environmental policies – forward-looking model



From figure 3 can be seen that the annual GDP loss differs substantially between the simulations. The *Shock-Sustainability* and *Gradual-Sustainability* simulations start with a GDP level equal to the base; this is logical, as environmental policy is not yet active in 1998 for these simulations. For the other two simulations, *Immediate-Sustainability* and *Above-Sustainability*, the GDP levels are instantaneously falling below zero and decrease slightly for each following period.

The shape of the GDP-curve for *Shock-Sustainability* is surprising: in stead of the expected smoothed pattern of consumption, GDP decreases sharply in 2015, after which it increases again, though less rapidly. The decrease in period 2015 itself is smaller than in the recursive-dynamic model, just as expected. The economic interpretation is that consumers know that environmental policy will be stricter from 2015 onwards, and they react by increasing current consumption in the early periods. Due to the time preference, this has a relatively large positive influence on total economic utility (which is optimised in this model). Naturally, this can only be achieved by decreasing their savings and hence decreasing investments (the reduction in investments compared to the base is more than 3% in the first period). This is reflected by a lower interest rate in the early periods. Then, immediately following the high consumption levels in the early periods, the savings/investment level increases rapidly, accompanied by lower consumption levels. These high investment levels are needed to assure long term growth of the economy and are induced by the low price of capital (the low interest rate). The combined effects of the changes in consumption and investment levels govern the changes in GDP.

Figure 4. Variables in Shock-Sustainability – Forward-looking model



The values of some of the main variables in the policy period are represented in Figure 4. The figure shows the high initial and then declining consumption levels and the initially low, but rapidly increasing investment levels. The introduction of the stricter environmental policy in 2015 is most clear in the investment level, that reduces significantly in only one period (but remains above the baseline; the level of investment in 2015 is 2.5% below the level in 2014). This drop in investment levels is immediately reflected in the consumption of Y2. Consumption of good Y1 only starts to increase a period later.

The rather surprising patterns of the variables in the policy period has an impact on the values of the variables in 2030, as can be seen from Table 6. Comparing the *Shock-Sustainability* and *Gradual-Sustainability* simulations, one can see that the same pattern occurs in both simulations. In the longer run, the temporary fluctuations in variables have faded out. Sector Y1 cannot sustain the high level of production, though the output loss is rather small. Investment levels do remain higher than in the base.

Table 6. Changes in main variables for 2030 and 2130 (forward-looking model)

(%-change of volumes)	*Shock-Sustainability*		*Gradual-Sustainability*		*Immediate-Sustainability*		*Above-Sustainability*	
	2030	2130	2030	2130	2030	2130	2030	2130
GDP	-0.26%	-0.75%	-0.42%	-0.80%	-2.23%	-2.75%	-0.80%	-1.02%
Priv. cons. of Y1	-2.33%	-2.16%	-2.58%	-2.22%	-2.54%	-2.49%	-0.89%	-0.88%
Priv. cons. of Y2	-0.81%	-1.01%	-1.06%	-1.04%	-2.10%	-2.38%	-0.74%	-0.88%
Production of Y1	0.50%	-0.26%	0.39%	-0.31%	-1.61%	-2.37%	-0.58%	-0.88%
Production of Y2	-0.29%	-0.79%	-0.49%	-0.83%	-2.16%	-2.70%	-0.77%	-1.00%
Investments	2.25%	0.32%	2.32%	0.23%	-2.19%	-3.88%	-0.80%	-1.46%
Abatement	14.94%	7.55%	14.71%	7.51%	12.87%	5.61%	4.59%	2.02%
CO_2 emissions	-80%	-80%	-80%	-80%	-80%	-80%	-40%	-40%
NO_x emissions	-80%	-80%	-80%	-80%	-80%	-80%	-40%	-40%

From Table 6 it also becomes clear that the effects of the *Immediate-Sustainability* simulation are quite different from the first two simulations. This simulation is characterised by an overall decrease in variable values.

In the forward-looking model specification, the *Above-Sustainability* scenario is more difficult to compare to the other simulations, as the long-run number of pollution permits available in the economy is higher in this simulation. This does not only influence the levels of the variables after the policy period, but will also have an impact on variables in the earlier periods, as the consumers do look at future utility as well as current utility when making decision on current consumption and savings levels.

In all simulations, the abatement expenditures increase rapidly in the policy period, but decrease afterwards, just as in the recursive-dynamic model. One reason for this is that abatement expenditures become cheaper over time: as labour productivity increases, the labour costs of the abatement measures decrease, leading to lower abatement expenditures.

4.6 Comparing the models

As indicated above, the possibilities of comparing the Steady-State model with the other two models is limited. Assuming that the results from the steady-state model can be interpreted as the long-term (stationary) values of the model variables, and assuming that the results from the recursive-dynamic and forward-looking models for 2130 also give the long-term (stationary) values, one can compare the steady-state results for the *Immediate-Sustainability* and *Above-Sustainability* simulations.

GDP is lower in the steady-state model than in the recursive-dynamic model (compare Tables 4 and 5). For the *Immediate-Sustainability* simulation, the difference is larger than for *Above-Sustainability*, indicating that as environmental strictness increases, the steady-state model is less and less capable of capturing the relevant (mitigating) effects these policies have in a dynamic context. Similarly, consumption and investment levels are also lower in the steady-state model.

Production levels differ between the models in quantitative terms, though in qualitative terms, the results are similar: both sectors are confronted with output losses, and sector Y2 a little more than sector Y1; the output losses are larger in the steady-state model. For abatement expenditures, the steady-state model leads to much higher levels than the recursive-dynamic model (2.5 to 3 times as high). This can to a large extent be attributed to the absence of increases in labour productivity in the steady-state model, so that the long-run marginal abatement costs are higher in the steady-state simulation.

The results for the recursive-dynamic and forward-looking models can be compared for all four simulations without much problems. In the *Shock-Sustainability* and *Gradual-Sustainability* simulations, the differences are significant between both models: GDP levels are higher in the forward-looking model than in the recursive-dynamic specification (compare Tables 5 and 6). The higher GDP in the forward-looking model is largely caused by higher consumption levels of good Y2; for Y1, the consumption levels are much closer together in both specifications.

In 2030, the production of sector Y1 decreases with almost 2% compared to the baseline, while in the forward-looking model this sector can even increase it's production. This difference does diminish over time, but production of Y1 remains higher in the forward-looking model throughout the whole period. For sector Y2, the differences are similar, with the exception that production of Y2 in 2030 is below the baseline in both model specifications. The most striking difference between both specifications is the effect of the policy on investments: in the recursive-dynamic model, investments decrease even more than consumption and production levels, while in the forward-looking model, investments are persistently above the baseline level (except in the first few periods). Apparently, in the recursive-dynamic the optimal path of consumption is relatively flat (with an instant fall in consumption levels when the stricter environmental policy is introduced in 2015), while in the forward-looking model, the variation in consumption levels is larger, thereby mitigating the effect of the policy shock.

The *Immediate-Sustainability* and *Above-Sustainability* simulations give less differences between the recursive-dynamic and forward-looking models. In qualitative terms, both models produce the same results, though there are some differences in quantities. In 2030, the forward-looking model gives higher values for GDP, consumption and production levels and investments than the recursive-dynamic model. But in 2130, the reverse is the case: almost all important variables, except for GDP, are (slightly) higher in the recursive-dynamic model. One reason for this may be that in the forward-looking model, the income levels in later periods are less relevant, as the present value of these income levels are very small (given the positive discount rate). In the recursive-dynamic model, such discounting of future income levels is not taken into account by the consumers.

Comparing the long-term properties of the policies in the recursive-dynamic and forward-looking model, the obvious difference is that in the forward-looking model, the *Immediate-Sustainability* simulation has significantly lower long-run values than the *Shock-sustainability* and *Gradual-Sustainability* simulations, while these are roughly equal in the recursive-dynamic model. Or, perhaps more precise, the *Shock-sustainability* and *Gradual-Sustainability* simulations have a smaller drop in GDP in the forward-looking model. In the forward-looking model, a stringent environmental policy in the early periods will have repercussions throughout the whole planning horizon, whereas in the recursive-dynamic model, the differences in environmental policy in the early periods have no significant impact in the longer term. This is a clear demonstration of the 'utility-increasing' effect of forward-looking behaviour: if there is more information on the future impacts of current decisions, the current decisions can be made more informed and so, discounted total utility increases.

In the very long run, this effect will dampen, as the long-run levels of equivalent variation are increasing in the recursive-dynamic model, while they are stable in the forward-looking model. This indicates that the recursive-dynamic specification results in a much slower adaptation process than when consumers have perfect foresight. The impact of these very-long-run equivalent variation-levels have however only a marginal influence on the net present value of all future GDP and utility levels.

5 Concluding remarks

In this article, three proto-type models are analysed, where the dynamic relations between production, consumption, pollution and pollution abatement are investigated. A multi-sectoral dynamic applied general equilibrium model is presented, with three different specifications of the dynamic issues: a steady-state specification, a recursive-dynamic specification and a forward-looking specification. In the model, there is a separate 'Abatement production sector', that provides the abatement techniques to the producers and consumers. Polluters have the (endogenous) choice between paying for pollution permits or investing in abatement; the extent to which this substitution is possible, and the characteristics of the Abatement producer, are derived from abatement cost curves.

It should be noted that the model provides insight into the least costs of achieving a predetermined environmental policy objective, but cannot calculate the optimal rate of pollution control, as the damages caused by pollution (the benefits of pollution control) are not taken into account.

A conclusion that can be drawn from the analysis is that the dynamic specification of the model is highly relevant. Not only are the numerical results influenced significantly by the model specification, the main interactions between economy and ecology can also be better specified in a dynamic context. Even with a simple specification of the abatement sector, there are dynamic interactions that influence the costs of abatement for the polluters, the price of the pollution permits and the economic impacts of environmental policy.

The major differences between a steady-state and a recursive-dynamic specification of the model are that the steady-state specification tends to produce a larger economic impact and higher abatement expenditures than the recursive-dynamic specification. However, the qualitative results of both specifications are similar for most variables.

The main difference between the recursive-dynamic and forward-looking specifications occurs when environmental policy is changing over time. Then, the perfect-foresight assumption in the forward-looking specification results in a distinctly different transition path from the current equilibrium to the new equilibrium growth path. If environmental policy is kept constant throughout the planning period, then there are still some differences between both specifications with respect to the transition paths, but these differences are much less prominent.

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