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Computable General equilibrium Models in Environmental and Resource Economics

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1. INTRODUCTION

The focus of this survey chapter is on the importance of general equilibrium interactions in assessing efficiency costs of environmental policies. Those interactions are relevant to the impacts of a wide range of government policies to control air pollution, deforestation or water quality. These policies raise the costs of output and the distortions in factor markets from pre-existing market imperfections and imply higher social costs than would be indicated by partial equilibrium models. Although computable general equilibrium models (CGE models) cannot be used to forecast business cycles, they can indicate likely magnitudes of policy-induced changes from future baselines, and they are indispensable for ranking alternative policy measures. Since these numerical models are based on assumptions concerning the economic development (elasticities of substitution, technical change, or the magnitude of exogenous variables) it would be misleading to base policy decisions on a specific numerical result. Rather, CGE models should be used to understand the reasons for particular results, to better frame the policy decisions, and to support the appropriate policy judgements. Using general equilibrium theory, economists can very often get a good idea of the welfare effect and of the qualitative results from a change in a given policy instrument. However, using theory alone, it is very often not possible to determine the signs of the net effects in general equilibrium interactions, to evaluate alternative environmental policy approaches with respect to their different impacts on the economy, and then to rank them according to their welfare effects. Theoretical models can account for general equilibrium issues but to be analytically tractable, simplicity is required whereas the numerically solved CGE models allow for greater complexity.

This chapter provides an overview of the use of CGE models in environmental economics. This overview is not meant to be exhaustive; rather we hope to illustrate the types of approaches we know of to give an impression of the scope of applying CGE models. We begin

[1] I wish to thank Henk Folmer, Larry Goulder, Tom Tietenberg and an anonymous referee for their many suggestions on an earlier version of this paper.

in Section 2 by emphasizing the importance of general versus partial equilibrium models and the advantage of CGE models compared to other macroeconomic models. The extension of a standard input-output model with fixed input-output coefficients to a CGE model with price-dependent coefficients is discussed in Section 3. In Section 4 we describe the development of investment decisions in the model of producer behavior, starting from recursive accumulation of capital under static expectation to the new generation of dynamic models where the manager of a firm accumulates capital over time in order to maximize the value of the firm. A similar approach can be chosen for a consumer who accumulates investment in consumer durables over time. This aspect is part of an intertemporal model of consumer behavior with several stages of budget allocation which we present in Section 5. Since environmental regulation may affect the international competitiveness, we show in Section 6 how in CGE models the trade pattern allows to adjust to environmental policy measures. Given the variety of modeling the labor market, we say only some words on this topic in Section 7. Another complex but very important topic is the modeling of technical change. Especially the long-term outcome from an environmental policy measure is very sensitive with respect to the assumption on the efficiency improvement in energy use, pollution abatement or waste disposal. Thus, we examine in Section 8 some approaches to incorporate technical change in CGE models. Also abatement technologies are an important aspect in environmentally orientated CGE models and we present some approaches to take into account this aspect in Section 9. Data required for doing CGE modeling are mentioned in Section 10. In section 11 we present several simulation studies in environmental economics based on the use of CGE models. First, we take the double dividend debate as an example for a CGE analysis. We present results from a CO_2 reduction policy for twelve EU member countries whose CGE models are linked by foreign trade (Section 11.1). In Sections 11.2-11.9 we review environmentally related CGE analyses on topics such as global warming, the costs of environmental regulation under different instruments, or joint implementation. Finally, we describe some models which look at a two-way link between the environment and economic performance (Section 12). In those models economic variables generate environmental externalities, but the latter ones also affect the quality of the former ones. Concluding remarks are made in the final section.

2. Partial Equilibrium Models, CGE Models and Macroeconomic Models

Policies aimed at significantly reducing environmental problems such as global warming, acid rain, deforestation, waste disposal or any other degradation of the quality of air, water, soil or land imply costs in terms of lower growth of GDP, a reduction in international competitiveness or in employment. The implied change in relative prices will induce general equilibrium effects throughout the whole economy. For this reason it is often useful to evaluate the effects of environmental policy measures within the framework of a computable general equilibrium (CGE) model. Although partial equilibrium models make it possible to estimate the costs of environmental policy measures, taking substitution processes in production and consumption as well as market clearing conditions into account, CGE models additionally allow for adjustments in all sectors, enable to consider the interactions between the intermediate input market and markets for other commodities or intermediate inputs, and complete the link between factor incomes and consumer expenditures. The link between environmental policy and the economy can rely on partial equilibrium models if feedback effects are not important or if a certain impact is to be demonstrated. However, one has to keep in mind that CGE analysis can yield very different results from what one would obtain from partial equilibrium. Policies that appear to improve efficiency in a partial equilibrium analysis emerge as reducing efficiency when model builders account for general equilibrium effects.[2] Researchers sometimes expect the net effect of the multitude of interdependencies and interactions within the economy to be zero when using a partial equilibrium model. However, if environmental policies raise the costs of output and thereby reduce real factor returns, they enforce the distortions in factor markets from pre-existing taxes and imply higher social costs than would be indicated by partial equilibrium analyses. A good example for illustrating the importance of general versus partial equilibrium models is the highly debated double dividend issue when a revenue-neutral carbon or energy tax is introduced. The open question is whether the positive substitution effect towards labor input will be outweighed by the negative output effect and by the adverse impact from new distortions on the factor market. Another example is to measure the effect of an emission tax on the performance of the economy. This policy raises marginal cost of production due to abatement expenditure and tax payments. Hence the firm will reduce its output under the present price level. If all firms in that industry react in the same way, the market supply function will shift to the left and the market price will rise. Now the firms will revise their output decisions. The higher domestic price will attract imports and will lower exports. The higher price in the environment-intensive industry will induce spillovers to other markets and industries which produce substitutes or complements. On the input side our firm will substitute labor, material

[2] See Krutilla (1999) on the usefulness of partial equilibrium models in the context of trade and the environment and Bovenberg and Goulder (2000) for a survey of the implications of general equilibrium interactions for environmental tax and regulatory policies.

and capital for the taxed energy input for keeping costs low. This affects the factor markets and factor prices. This line of reasoning shows the substantial difference between a partial equilibrium analysis and a CGE analysis.

The impact of an environmental policy could also be analyzed with macroeconomic models based on Keynesian theory, on monetaristic approaches, on supply side models, on models with an optimization framework (optimal control, non-linear dynamic optimization) or on dynamic input-output models.[3] These models focus on the impact of environmental policy on unemployment, on inflation, on disequilibrium in some markets, on cyclical developments, on convergence and stability, on long-run growth, and on forecasting. A disadvantage of macroeconomic models is their heterogeneous theoretical underpinning. Since in recent years macroeconomic models tend to incorporate microeconomic elements, the difference between CGE models and macroeconomic models became less clear. In principle, a CGE model is a member of the class of macroeconomic models which has as its theoretical underpinning the application of an Arrow-Debreu general equilibrium framework. The commonly made assumption of an underlying optimizing behavior of all agents explains why microeconomic theory and general equilibrium theory have strongly increased their relevance for policy analysis. The outcome of a policy simulation is not generated from a black box but can be traced back to rational behavior. CGE models can provide answers on economic effects of changes in tax rates or of the introduction of new taxes or subsidies in a coherent and consistent way. They are superior to traditional macroeconomic models when the source and the effects of market inefficiencies are to be investigated or when excess burdens caused by price distorting measures are to be demonstrated. They are the appropriate tool to answer important policy questions such as structural adjustments, tax reforms or trade liberalization. CGE models are therefore primarily focused on long-run impacts whereas macroeconomic models are more appropriate to shed light on the transition from the old equilibrium to the new one.

3. From Input Output Models to CGE Models

Leontief's input output analysis is based on an input output table and on inter-industry input output production relations to model the exchange of commodities by agents. A static input

[3] See Ierland (1999) for a survey on macroeconomic modeling and the environment, and Duchin and Stenge (1999) for a survey on input-output analysis of the environment.

output model describes the relationship between supply X_i of an industry i and intermediate demands of all industries j (j = 1, ..., n) for goods from industry i, X_{ij}, and final demand FD_i:

(1) $$X_i = \sum_{j=1}^{n} X_{ij} + FD_i \quad , \quad i = 1,...,n\,.$$

For primary factors labor L and capital K, supply $\bar{L}(\bar{K})$ should be equal to the sum of the demand $L_j(K_j)$ by all industries:

(2) $$\bar{L} = \sum_{j=1}^{n} L_j \qquad \bar{K} = \sum_{j=1}^{n} K_j\,.$$

Under the assumption of fixed Walras-Leontief input coefficients,

(3) $$X_{ij} = a_{ij} \cdot X_j \quad , \quad i, j = 1,...,n$$

(4) $$L_j = a_{Lj} \cdot X_j \quad , \quad K_j = a_{Kj} \cdot X_j \quad , \quad j = 1,...,n$$

(1) and (2) can be written as

(5) $$X_i = \sum_{j=1}^{n} a_{ij} \cdot X_j + FD_i$$

(6) $$\bar{L} = \sum_{j} a_{Lj} \cdot X_j \quad , \quad \bar{K} = \sum_{j} a_{Kj} \cdot X_j\,.$$

Given final demand, (5) can be solved for the output levels X_i and (6) then gives the demand for the primary inputs. Prices PX_i can be determined by using the identity

$$PX_j \cdot X_j = \sum_{i=1}^{n} PX_i \cdot X_{ij} + PL \cdot L_j + PK \cdot K_j$$

and then (3) and (4):

(7) $$PX_j = \sum_{i=1}^{n} PX_i \cdot a_{ij} + PL \cdot a_{Lj} + PK \cdot a_{Kj}$$

where prices for labor and capital are exogenous. The critical features of this model are that input coefficients do not depend on prices and that prices, calculated as an arithmetic mean with input coefficients as weights, have no impact on the economy.

The idea to derive price dependent input coefficients as factor demand functions of the neoclassical production theory goes back to Samuelson's (1951) "non-substitution theorem". In a path-breaking paper Samuelson (1953) studies the causal relationship between prices and quantities and proves the duality of cost and production functions. The dual characterization of a technology, also shown by Shephard (1953), permits as Shephard's lemma to derive cost-minimizing input coefficients as partial derivative of a unit cost function of the output of an industry. First order conditions of producer behavior had not to be solved explicitly for the quantities as function of prices (if this was possible at all) and, in addition, those unit cost functions as a dual characterization of the technology proved to be useful to determine prices. Unlike inter-industry input-output models and other earlier economy-wide planning models, household factor income and expenditures are linked in a theoretically appropriate manner. As will be seen next, the input-output technology is typically embedded in CGE models to characterize inter-industry transfers.

In a dual CGE approach the technology of a cost minimizing industry is characterized by a cost function *C*,

(8) $$C_j = C_j(X_j, w, PL, PK) \qquad j = 1,..., n$$

where *w* is the price vector of intermediate inputs. The observed costs are

$$C_j = \sum_{i=1}^{n} w_i \cdot X_{ij} + PL \cdot L_j + PK \cdot K_j .$$

Under the assumption of constant returns to scale, $c_j = C_j(1, w, PL, PK)$ is the unit cost function and $C_j = X_j \cdot c_j(w, PL, PK)$.

From Shephard's lemma we derive demand functions as input coefficients:

(9) $$\frac{X_{ij}}{X_j} = \frac{\partial c_j(\cdot)}{\partial w_i} \quad , \qquad i = 1,\dots,n \,, \qquad \frac{L_j}{X_j} = \frac{\partial c_j}{\partial PL} \,, \qquad \frac{K_j}{X_j} = \frac{\partial c_j}{\partial PK} \,.$$

Assuming profit maximization under perfect competition $(PX = MC)$:

(10) $$PX_j = c_j(w, PL, PK) \,.$$

This price equal average cost condition can be employed to determine the system of n output prices. Since the price vector w of intermediate inputs is exactly the price vector $(PX_1,\dots,PX_n)$ of output prices, equation (10) for industry j is:

(11) $$PX_j = c_j(PX_1,\dots,PX_n, PL, PK) \quad , \qquad j = 1,\dots,n \,.$$

This system of n prices can be solved, given the prices of labor and capital. In order to determine the output levels X_j which are influence by the price system, we substitute $X_{ij} = X_j \dfrac{\partial c_j(\cdot)}{\partial PX_i}$ from (9) for X_{ij} in (1) and obtain

(12) $$X_i = \sum_j X_j \frac{\partial c_j(\cdot)}{\partial PX_i} + FD_i \quad , \qquad i = 1,\dots,n \,.$$

This system of n equations in the n unknown X's can be solved, given final demand. A CGE model is therefore a system of linear and nonlinear equations that is solved to simulate market equilibrium. It includes equations describing consumers' and producers' supply and demand behavior that are derived explicitly from conditions for profit or utility maximization (see section 4), and market clearing conditions in product and input markets (see section 6). In this dual or cost-driven form, pioneered by Johansen and Jorgenson,[4] Leontief's input output model is a special case if consumer behavior and factor market are ignored. If the unit cost function in (11) is an arithmetic mean of input prices, as given in (7), then (12) is identical with (5), the basic Leontief model.

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[4] For a survey on the development of CGE modeling see Shoven and Whalley (1984), Robinson (1989), Bergman (1990a) or Conrad (1999).

CGE models based on the primal approach to production have been used by Shoven and Whalley (1973,1984). In the primal problem formulation, the agent determines supply quantities as a function of the market prices of commodities, while in the dual problem the supplier is setting the market price of the commodity, he is supplying by using the inverse supply function, i.e. price equal to marginal cost. In the primal problem form, demand as well as supply depend explicitly on prices which are determined by equating demand and supply. In the dual problem form, the supplier receives the market price of the commodity from average cost pricing. Demand depends explicitly on prices and determines the quantity to be supplied. Supply enters marginal cost which influence the price. In principle, however, it doesn't matter which approach is used if the equilibrium is unique and the forms of the cost and production functions used are self-dual (Cobb-Douglas or CES specifications).[5] The Shoven-Whalley type of models have their roots in applied welfare economics while the Johansen-Jorgenson type of models originate from input-output analysis (see Johansen (1979); Hudson and Jorgenson (1974)).

The choice of specifying functional forms for production or cost functions depends on adopting the econometric approach or the calibration approach to CGE modeling. The econometric approach requires time series or cross-sectional data for estimating the unknown parameters statistically. Calibration may make use of a mix of econometric results and other data taken from the literature. When choosing the econometric approach, flexible functional forms like the translog specification (Jorgenson and Wilcoxen, 1990a, b; Hazilla and Kopp, 1990) or the Generalized Leontief specification of cost functions (Glomsrod et al., 1992) can be used. The estimation procedure of the unknown parameters is based on a multi-level nest of input compositions. At the "top" level, there are two inputs, for instance energy and non-energy, or four inputs, say labor, capital, material and energy. Depending on the focus of the study, land instead of energy can be included in this nesting, or commodities from agriculture or forestry, respectively. At the "bottom" level, demand for aggregated energy, material or for transportation is further divided into its components using nested flexible sub-functions. Agriculture, e.g., can be decomposed into program crops, livestock and dairy, and all other agricultural production if

[5] I will also not discuss theoretical issues like uniqueness of a general equilibrium or externalities as a source of nonconvexity. Under concavity - convexity assumptions Pareto optimality in a basic general equilibrium model with externalities exists and is unique (see Baumol and Oates, 1988, Ch. 4). The existence of a competitive solution that is consistent with any particular Pareto optimum has been explored in an extensive literature. The question is, however, whether in GE models calibrated on real world data, nonexistence is a serious problem. A proof of existence of, and computational procedure for finding, a general equilibrium with taxes were derived by Shoven and Whalley (1973). A more serious problem is that any detrimental externalities can produce non-convexity. This breakdown in the concavity-convexity conditions may result in several local optima so that prices may give the wrong signals - directing the economy away from the social optimum.

the user of a CGE model wishes to illustrate some of the difficulties of coordinating agricultural and environmental policies (Hrubovcak et al., 1990). The common approach to CGE modeling is to calibrate the parameters of the model so that one year observations are sufficient. The prefered specification is a series of nested CES functions but with fixed input coefficients for some input components (e.g. Bergman, 1990b, Capros et al. (1996) or the GREEN-model). In the CES approach, the elasticity of substitution will be guessed, and the distribution parameters depend on the particular year chosen for calibration. The elasticities of price-induced substitution are key parameters and will affect the economic costs and environmental benefits from stricter policies towards sustainable development. In general, input categories and nests in a nested production structure should be selected according to the focus of the model. Those nests one would use for an energy oriented model may not be the same as for a trade and environmental analysis in a developing country that depends on agriculture, fishery and forestry.

To demonstrate the production/cost nesting, let us assume that the first m prices in (11) are prices of fossil fuels (gas, oil, coal). Then the unit cost function PE_j of industry j for fossil energy is $\left(j \in \{1,...,m\} \right)$:

$$PE_j = CES_j \left(PX_1,...,PX_m \right) = \left[\sum d_i^s \cdot PX_i^{1-s} \right]^{\frac{1}{1-s}} \qquad (13)$$

where s is the elasticity of substitution and the d_i's are distributional weights which indicate the relative significance of the inputs (we omit an index j on d_i and s for simplifying the notation). This cost function is dual to a CES sub-production function

$$E_j = \left(\sum d_i X_{ij}^{-r} \right)^{-\frac{1}{r}}$$

where r is the substitution parameter $\left(s = \dfrac{1}{1+r} \right)$. Using Shephard's lemma, input coefficients for fossil fuels are

$$\frac{X_{ij}}{E_j} = \frac{\partial\, CES_j(\cdot)}{\partial\, PX_i} = d_i^s \left(\frac{PE_j}{PX_i} \right)^s \quad , \qquad i=1,...,m. \qquad (14)$$

From (9) we get, using Shephard's lemma with respect to the price PE

(15) $$\frac{E_j}{X_j} = \frac{\partial\, c_j(PE, PX_{m+1}, \ldots)}{\partial\, PE}.$$

If we multiply (14) by (15), we obtain price dependent energy input coefficients as a subset of the coefficients derived in (9).

4. Producer Behavior

Given the basic neoclassical approach to model producer behavior in an inter-industry framework, CGE models differ from one another in dealing with the following issues: expectations and planning horizon, the optimal choice of investment with or without adjustment costs, the treatment of technical change, and the incorporation of abatement activities. In this section we deal with producer behavior with respect to investment decision and in separate sections with respect to technical change and abatement technologies.

In the first generation of CGE models producers were regarded as having static expectations and the dynamics are modeled as a recursive accumulative procedure. The capital stock is fixed in the short run and variable in the long run. Investment is neither determined by savings behavior of private households nor is it determined by the behavior of a manager who maximizes the value of the firm (the Tobin (1969) q-theory of investment). Especially in large-scale CGE models investment of the firm is determined by optimal capital costs in the long run, expectations about future growth of demand for a firm's product and static expectation about its future prices. An adjustment factor determines the percentage a firm wishes to invest in order to narrow the gap between the size of its "desired" capital stock and its current level. If, however, agents have myopic expectations, they expect future prices to be the same as current ones. Decisions in each period of the transition phase to a new long-run equilibrium will then deviate from optimal decisions if a policy change has affected prices. In such models the requirements for actions in a future period (e.g. global warming) will not alter the nature of environmental decisions before the requirements come into effect. In the new generation of fully dynamic CGE models investment decisions are based on forward looking expectations (rational or perfect foresight) and on intertemporal optimization behavior. In addition, adjustment cost functions express the notion that installing new capital necessitates a loss of current output. The coordination of intertemporal savings behavior and investment decisions occurs on perfect capital markets. In models with perfect foresight, the cost estimates of an environmental policy can be lower than for the same model with no foresight because there will be no early, and hence costly, retirement of the capital stock.

An important advantage of an explicit intertemporal optimization framework is that the necessary ex-post equality between investment and savings can be warranted, which is not the case in a backward looking capital accumulation approach (see Dewatripont and Michel (1987)). Therefore, no closure rule has to be chosen, that is, none of the constraints of the model must be relaxed to find a solution when all markets are in equilibrium. In most static CGE models the identity of private gross domestic production from the flow of cost approach with the flow of product approach has been used to choose a residual variable for closing the model. Such a variable could be investment, the public budget or the balance of trade.[6] The ex-post identity of gross investment to net savings (household savings, government budget deficit and current account balance) serves as a closure rule e.g. in Hudson and Jorgenson (1974), GREEN or in some versions of GEM-E3.

In the new generation of dynamic models the focus is on how a manager should accumulate capital over time in order to maximize the value of the firm.[7] Let p be the firm's profit (or a restricted profit function), then the following cash-flow identity links the firm's sources (left hand side) and uses of revenues (right hand side)

$$p + BN + VN = DIV + PI \cdot I$$

where *BN* is new dept issue, *VN* new share issue, $PI \cdot I$ are investment expenditure and *DIV* are dividend payments. New share issues are residual because dividend payments are assumed to be a constant fraction, *a*, of profit net of economic depreciation, and new debt issue to be a constant fraction, *b*, of the value of net investment:

$$DIV = a \cdot (p + (PI - PI_{-1})) \cdot K - d \cdot PI \cdot K$$
$$BN = b \cdot (PI \cdot K_{+1} - PI_{-1} \cdot K)$$

where d is the rate of economic depreciation.[8] Arbitrage possibilities compel the firm to offer

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[6] For alternative closure rules see Dewatripont and Michel (1987).

[7] See Bovenberg and Goulder (1991) on introducing intertemporal features in CGE models. For CGE models where investment decisions are based on maximizing the value of the firm see Goulder (1995), Goulder and Summers (1989), Keuschnigg and Kohler (1994) or Vennemo (1997).

[8] Several assumptions are possible about the dividend and financing policy of a firm which we will not discuss here.

its stockholders a rate of return comparable to the interest rate i on alternative assets:[9]

(16) $$DIV + (V_{+1} - V - VN) = i \cdot V \ .$$

The return before tax to stockholders consists of the current dividend plus capital gain on the equity value *(V)* of the firm net of the value of new share issues. This return must be comparable to the return from an investment of the same value at the market rate of interest, *i*. Forward substitution of the basic arbitrage condition yields the following expression for the firm's equity value as the discounted value of dividends less share issues:

$$V_t = \sum_{s=t}^{\infty} \left[DIV_s - VN_s \right] \cdot \prod_{u=t+1}^{s} (1 + i_u)^{-1}$$

The manager maximizes V subject to the capital accumulation condition by choosing optimally in each period the levels of labor, intermediate inputs and of investment.

There are theoretical difficulties in extending CGE models but the effort seems to be worthwhile to end up with useful policy models. However, it is important to proceed with caution, adding at each step only as much complication as is needed, and retaining a clear view of the causal mechanisms at work.[10]

5. Consumer Behavior

In most CGE models the focus of the analysis is on efficiency issues, and all consumers are then aggregated into a single representative consumer. This infinitely lived consumer with perfect foresight maximizes in year t the discounted sum of intra-period utility from "full consumption" FC consisting of consumption goods and leisure:[11]

$$U_t = \sum_{t=t}^{\infty} (1+s)^{t-t} \frac{s}{s-1} FC_s^{\frac{s-1}{s}}$$

[9] We assumed that all tax rates on capital income are of equal size.

[10] An example in this context is the issue whether capital is assumed to be perfectly mobile across sectors (as in Jorgenson and Wilcoxen (1990b)), or imperfectly mobile (because of adjustment costs (as in Bovenberg and Goulder (1991)). This can be very important to how the economy responds to a policy shock, and to the welfare impacts.

[11] This is only one (frequently used) way to model intertemporal consumer behavior.

The parameter s is the intertemporal elasticity of substitution in full consumption and s is the rate of time preference. Full consumption is a quantity index in the form of an intraperiod aggregate of consumption of goods (C_t) and leisure (LJ_t):

$$FC_t = FC(C_t, LJ_t)$$

The maximization of the weak separable intertemporal utility function is subject to a budget constraint that restricts the present value of expenditures not to exceed the present value of lifetime wealth endowment. This endowment consists of the present value of wages, the imputed value of leisure time, of net transfer, and of the value of current non-human wealth. The determination of full consumption can be seen as the first stage in the allocation procedure of a consumer. At the second stage the consumer maximizes an intra-period utility function given the full income the consumer has decided to spend in each period. The allocation is usually based on a within period expenditure function with full consumption as an indicator of within period utility. At this stage the consumer decides how to allocate full consumption between consumption of goods C_t and of leisure time. The difference between the quantity of leisure consumed and the household's total time endowment determines the quantity of labor supplied. Saving is also determined at this stage and is the difference between current income from the supply of capital and labor services and personal consumption expenditures. At the final stage of the budgeting process, consumption is allocated into several consumption categories. The allocation is normally between a composite of non-energy goods and a composite of energy goods. Then different non-energy goods have to be chosen as well as different energy goods. The several consumption categories are then being transferred into consumption by product according to the industry classification used.

Since environmental regulation affects the use and purchase of consumer durables such as cars, electric appliances, and heating, a model of consumer behavior should integrate demand for durables and for non-durables. Demand for non-durables and for services from durables has to be reconciled with investment demand for durables to modify the stock of durables towards their optimal levels. Such an approach permits to model the impact of an energy or gasoline tax on growth and on the age of the stock of durables.[12] Since non-durable goods like gasoline or electricity are linked to durable goods such as cars or electric appliances, prices of durables are

[12] Conrad and Schröder (1991b) developed an integrated framework of consumer demand for 20 non-durable goods like food and services, and for three durable goods: cars, heating and electric appliances.

stated in terms of user costs which include all costs of using durables.[13] The approach is based on the notion of a variable expenditure function $e(u, p, z)$ which gives minimal expenditure for non-durable goods given the utility level u, the price vector p of the non-durable goods and the vector z of the quasi-fixed stock of durables.

The optimal stock of the durables can be derived from an intertemporal minimization of expenditures. These expenditures consist of expenditures for non-durables, of purchases of new durables as net investment, of purchases for replacement, and of taxes on durables like a motor vehicle tax. If we include the aspect of adjustment costs, the long-run problem facing the consumer is to minimize the present value of the expected sum of variable expenditures, the purchase costs of quasi-fixed assets, and adjustment costs. The analytical solution is similar to the firm's decision on investment facing a variable cost function with quasi-fixed capital.

If consumer behavior is based on a representative consumer then one of the restrictions of such an approach is that preferences are identical for all consumers. However, expenditure patterns differ with demographic characteristics of individual consumers and therefore environmental policies have different impacts on different households, depending on the size of their stock of consumer durables. In assessing the distributional impacts of policies to restrict air pollution, a disaggregation into several types of households is potentially useful. To capture differences among social groups of households, Jorgenson and Wilcoxen (1993) have subdivided the household sector into demographic groups that differ by characteristics such as family size, age of head, region of residence and urban versus rural location.

Especially in large-scale models consumers have myopic expectations and no perfect foresight. They expect future prices to be the same as current ones. However, as a policy change will induce prices to change, the consumer makes a mistake in each period in the transition phase to a new long-run equilibrium. While with rational expectations, consumers readily adjust their behavior to the announced policy change, consumers with myopic expectations do not adjust their behavior only until the policy is enacted. In modeling perfect foresight there are three options which can be considered. Besides the Ramsey type model, which assumes an infinitely living representative consumer, there is the Blanchard type approach where different generations are alive each period. Each generation has the same constant death probability independent on age. The third type is a model of the Auerbach and Kotlikoff (1987) type where different generations are alive in each period and the individuals face different death probabilities dependent on their age. To my knowledge no CGE model

[13] The same concept is used in the GEM-E3 model.

exists with an Auerbach/Kotlikoff type of modeling the household sector whereas a Blanchard type model has been used (e.g. Keuschnigg and Kohler (1994)).

Common specifications for the intra-temporal allocation of consumption into categories are the linear expenditure system, nested CES or translog demand functions. A linear expenditure system based on a restricted expenditure function with consumers durables as quasi-fixed stocks can be found in Conrad and Schröder (1991b). Calibration of a linear expenditure system requires information on all income elasticities to calculate the parameters of the budget shares as well as information on all own-price elasticities to calculate the minimum required quantity of the good.

6. Foreign Trade, Domestic Supply and Demand

If all countries implement a more stringent environmental policy, the impact on their GDPs and relative prices of goods will be different in each country. As a result trade patterns and domestic production will change. These effects will be more significant if a unilateral action is taken by one of the countries, which adversely affects the international competitiveness. Since the costs of environmental policies will decline as the number of countries implementing them increases, it is important to model the impact on international competitiveness by endogenizing foreign trade. Most CGE models allow the trade pattern to adjust to environmental policy measures. Since perfect specialization is rarely observed in reality and since two-way trade prevails, the Armington (1969) assumption is widely adopted to model intra-industry trade. Under this assumption, domestically produced goods and imported goods are not perfect substitutes. We next describe a CGE approach to model trade, domestic supply and total demand by adopting the small open economy framework, i.e. the domestic economy is considered as sufficiently small. This assumption implies that the domestic economy does not affect international prices.[14]

Firms substitute between domestic, X, and foreign goods, IM, to minimize the cost of obtaining a given Armington composite good, Y. The dual approach is based on a unit cost function

$$PY = CES(PX, PIM) \tag{17}$$

[14] The GEM-E3 model is not based on that assumption (see Capros et al. (1996) and Conrad and Schmidt (1998)).

where PY is the price of the aggregate composite, and *PX(PIM)* is the price of obtaining the domestic (foreign) good. From this cost function the share for the domestic good in the composite good is derived by Shephard's lemma:

(18) $$\frac{X}{Y} = cx \cdot \left(\frac{PY}{PX} \right)^{s}$$

as well as the aggregate import in the composite good[15]

(18) $$\frac{IM}{Y} = (1 - cx) \left(\frac{PY}{PIM} \right)^{s}$$

Y is determined from the input output part of the CGE model, i.e. from

(20) $$Y_i = \sum a_{ij} X_j + FD_i = \sum a_{ij} \cdot \left(\frac{X_j}{Y_j} \right) Y_j + FD_i$$

with the price dependent share X_j / Y_j from (18). Equations (18) and (19) therefore allocate Y to X and IM, and (17) determines PY. If CGE models are linked by trade flow matrices, then PIM has to be specified as a unit cost function in import prices (equal to export prices) of the trading partners as done in the GEM-E3 project. Here[16], $PIM = PEX_{row}/ex$ where PEX is the export price of the rest of the world (row) (exogenous) and the exchange rate ex is in \$ per Euro (exogenous). This assumption implies that the foreign import supply function is horizontal at PEX_{row}.

For determining domestic export supply, firms maximize revenue $PX \cdot X + PEX \cdot EX$ from domestic, X, and foreign supply EX subject to a constant return to scale CET (constant elasticity of transformation) function for the composite good Y (determined by (20)) as a function of X and EX. Using again the dual approach of a CET unit revenue function

(21) $$PY = CET(PX, PEX)$$

[15] To simplify the notation we omit an index *j* for the industry.
[16] In our presentation we omit taxes and customs duties.

we obtain supply functions using Hotelling's lemma, i.e. differentiating (21) with respect to the product prices:

(22) $$X = Y \cdot g_X \cdot \left(\frac{PY}{PX} \right)^{s_T}$$

(23) $$EX = Y \cdot g_{EX} \cdot \left(\frac{PY}{PEX} \right)^{s_T}$$

where $s_T < 0$ is the elasticity of transformation and the g 's indicate the significance of the outputs. Equating the export equation (23) with import demand of the *ROW* (see IM_{row} in (24) below) gives the price *PEX*. Since *PY* has been determined by (17), (21) can be solved for PX. Then X in (22) can be calculated. In order to model import demand by the *ROW*, we proceed as in (17)-(19) by adding an index row to all variables. Dividing the symmetric equation of (19) by (18) yields import demand of the row

(24) $$IM_{row} = Y_{row} \cdot g_{row} \left(\frac{PY_{row}}{PIM_{row}} \right)^{s}$$

where $PIM_{row} = PEX/ex$ and *PEX* determined as mentioned above. World market prices PY_{row} and sectoral output levels Y_{row} of the *ROW* are exogenous. One of these prices serves as numeraire. Note that the foreign export demand function is not horizontal but is declining in *PEX*.

We finally can calculate the trade surplus/deficit *TS* by commodity

(25) $$TS = PEX \cdot EX - PIM \cdot IM \ .$$

By summing up over all commodities, the total trade surplus/deficit can be calculated. If the exchange rate is assumed to be exogenous (as in GEM-M3), the current account is not balanced and will change with the policy simulation. Instead of a residual as a world closure, an alternative is to fix *TS* and make the exchange rate endogenous. The models are closed by budget constraints, market clearing conditions and macroeconomic balances based on the Social Accounting Matrix. These equations include all kinds of taxes, subsidies and transfer payments. They summarize incomes and expenditures of private households, of the government and of the rest of the world. For the government the deficit/surplus could be held fixed and one of the taxes is allowed to adjust, or it could be determined endogenously as a residual. Finally, some variables have to be set at an exogenous level because we do not know how the world oil market functions (price of crude oil is exogenous) or because the impact of technical change is uncertain.

7. Labor Markets

The specification of the labor market could be crucial to the discussion on the effect of environmental policy on employment. A labor market policy of recycling tax revenues from an environmental tax to lower employers' non-wage labor cost depends on how the labor market is modeled. Non-competitive labor markets could provide another potential channel for the so called "double dividend" (see section 11.1). In most CGE models the labor market is perfectly competitive and the wage rate adjusts so that supply equals demand. Proost and Regemorter (1995) consider several income groups and different regimes for the labor market to test the double dividend hypotheses empirically including equity aspects. Labor supply is fixed and they consider a case with flexible wages and one with fixed real wages. The efficiency gain that can be made by using the tax revenue from an environmental tax to reduce existing distortions from high taxes on labor depends crucially on how flexible labor supply is. In most static models a simple labor supply curve for a skill category is implemented where labor supply is a function of the real wage rate:

$$L^S = \bar{L} \cdot \left(\frac{PL}{PY} \right)^h .$$

If the supply elasticity h is zero, labor supply is fixed $(\bar{L})$ and if it is infinite, the real wage rate is fixed. In this case, the labor supply equation is dropped from the system and the labor market equilibrium equation states that labor demand is always met by supply. Suppliers will freely supply all labor demanded at the fixed wage and a labor supply function can be used as a side equation to compute involuntary unemployment. If the labor supply curve is not flat, the condition $\sum_j L_{j,l}^d = L_l^s$ determines the equilibrium wage rate for a skill category *l*.

In intertemporal models the representative agent allocates full consumption between goods and leisure, determining personal consumption expenditure, labor supply, and savings. The price of labor is determined (e.g. in McKibbin and Wilcosen (1992)) by assuming that it adjusts according to an overlapping contracts model where nominal wages are set based on current and expected inflation and on labor demand relative to labor supply. In the long run labor supply is given by the exogenous rate of population growth, but in the short run the hours worked can fluctuate depending on the demand for labor. Then for a given nominal wage, the demand for labor will determine short-run unemployment.

Some model builders do sensitivity analyses to test whether the computed results depend on the labor market specification. Boehringer et al. (2000) incorporate some features of wage bargaining in the presence of initial unemployment in order to represent labor market imperfections. A Phillips curve concept is used to model the empirical evidence that high unemployment rates weaken the level of bargaining power by unions, which in turn implies lower real wages (see also GEM-E3 or Carraro and Galeotti (1994)).

8. Technical Change

It is well-known that the outcome from an environmental policy measure in response to mitigate global climate change is very sensitive to the assumption made on the rate of energy efficiency improvement. However, technical progress is in general considered to be a non-economic, exogenous variable in economic policy models. This is not very satisfactory because the neglect of induced technological progress may lead to an overestimation of the costs of greenhouse gas reduction or of the contribution of traffic to air pollution. An inadequate representation of policy driven technical change in the models will also result in an understatement of the advantages of market-based instruments. In the field of industrial organization partial models have been developed to endogenize the process from R&D expenditure to invention and innovation, and then to diffusion of a new process or product. These models seem, however, not appropriate for implementation and calibration.

The technological change process is usually initiated by public or private R&D and diffuses by “learning by using”, “learning by doing” and by networking. These processes are not easy to capture in a neoclassical framework because they have evolutionary elements. In most models technological parameters, representing e.g. efficiency or emission reduction potentials, are treated as inputs and not as results of the technological change process. The impact of technological change on processes, products and on emissions can not be modeled with only a few equations. Emission reduction of air pollutants can be achieved by fuel substitution (non-energy for energy or within energy inputs), by efficiency improvement in power generation, and by the energy user. The potential for emission reduction can focus on energy use per unit of production or on emissions per kWh. Stages of the techno-economic development have to model incentives and costs of R&D, implementation costs (information and operating costs), commercialization, wide-scale diffusion, appropriability, barriers to market penetration, the technological infrastructure and the scope for future efficiency improvement of established versus novel products. For reducing greenhouse gas emissions, e.g., there are many technologies or means which could be introduced in a model: fuel substitution to less carbon-intensive fuels, renewable energy, advanced power generation cycles, transmission improvements, end user efficiency improvement or carbon sequestration (e.g. by biomass greening). It is obvious that it is not possible to model all those measures within a CGE framework. Bottom-up firm specific models (e.g. the EU models MURE, MARKAL, EFOM) try to capture technological change by linking detailed technically oriented submodels to economic models in order to endogenize technical change. However, in recent years there have been significant new developments in CGE modeling of endogenous technological change. Until recently, the following four main approaches were used to incorporate technical progress in CGE models:

- a partially endogenous treatment of technical progress initiated by Jorgenson and Wilcoxen
- autonomous energy efficiency improvement (input saving technical change)
- the vintage composition of the capital stock
- the transition to backstop technologies

In Jorgenson and Wilcoxen (1990), and later in the G-Cubed model of Wilcoxen and McKibbin (1992), technological development is partly endogenized by the specification of productivity growth as a function of the prices of all inputs of an industry. In this approach, substitution away from polluting inputs can affect the rate of productivity growth. A decrease in an industry's productivity level will raise the price of its output relative to its input prices, i.e. the industry will become less competitive. If the bias of technical change is input of type i using and the price of such a pollution intensive input increases (e.g. by a tax), then cost reduction due to productivity growth will be reduced.

The translog unit cost or price function of the prices of all the inputs of an industry j is

$$\ln c_j = \alpha_0^j + \sum \alpha_i^j \ln p_i + \alpha_T^j \cdot t + \frac{1}{2} \sum \beta_{iK}^j \cdot \ln p_i \cdot \ln p_K + \sum \gamma_{iT}^j \ln p_i \cdot t + \frac{1}{2} \gamma_{TT}^j \cdot t^2$$

where *t* is time and an index of technology. Input-coefficients derived by Shephard's lemma are:

$$\frac{x_{ij}}{x_j} = (\alpha_i^j + \sum_k \beta_{ik}^j \ln p_k + \gamma_{iT}^j \cdot t) \frac{c_j}{p_i}$$

where γ_{iT} indicates the bias of technical change. The rate of cost reduction due to productivity growth is

$$\frac{\partial \ln c_j}{\partial t} = \alpha_T^j + \sum_i \gamma_{iT}^j \ln p_i + \gamma_{TT}^j \cdot t$$

and is expected to be negative. If the bias of technical change is input *i* using, i.e. $\gamma_{iT} > 0$, and the price of this pollution intensive input increases $(\Delta p_i > 0)$, then cost reduction due to productivity growth $\left(\frac{\partial \ln c_j}{\partial t} \right)$ in industry *j* will become smaller, because $\gamma_{iT} \cdot \ln \Delta p_i$ is added to the negative cost reduction parameter α_T^j (in the base year: all $p_i = 1,\ t = 0$). Technological development is treated only partially in this model because an autonomous trend is included which interacts with the prices of intermediate inputs. There is price induced productivity growth in the model which affects input shares. But technological change is not endogenized in terms of reversing a bias, leading to new vintages of durable goods, to new products or to different qualities or major breakthroughs. The models by Glomsrod et.al. (1992) or by Hazilla and Kopp (1990) endogenize fuel specific technical change in a similar way, i.e. as an incentive for substitution only.

Autonomous energy efficiency improvements (AEEI) are more difficult to estimate than those that are induced by price increases. AEEI decouples resource demand and economic output, and so yields resource-saving technical change. In the dual cost function approach some input prices are multiplied by a function representing price diminishing technical change, i.e. $P_i(t) = P_i(t-1) \cdot \exp(-\gamma_i \cdot t), \quad \gamma_i > 0$. Non-price induced efficiency improvements may be induced by changes in public policy like a mandatory doubling of average fuel efficiency of automobiles during the course of ten years. Manne and Richels (1990) introduce those exogenous efficiency improvements, for example. They also include explicit carbon removal technologies if carbon tax rates are large. Their production function also allows for the possibility of "autonomous (costless) energy efficiency improvements" which reduce the share of energy in GNP over time. A factor for autonomous energy efficiency improvement integrates all non-price induced changes in energy intensity and therefore represents the efficiency effect of technological, structural and political objectives (e.g. voluntary agreements). This approach emphasizes to show the **effect** of technical change but can not model aspects like innovation, adaptation or diffusion. If an environmental policy induces technical change, e.g. triggers emission or resource saving technical change, it would reduce the cost of achieving a given abatement or resource conservation target. Most CGE models, however, assume no difference in the pattern of technical change between the base case and the policy case. This probably leads to an upward bias in the cost estimate of that policy.

An alternative approach to incorporate technical change is the use of capital vintages involving different technologies. The differentiation of technologies can have effects on the form of the production function, on the input structure, or on flexibility (different elasticities of substitution for the vintages). With new vintages substitution possibilities among production factors are higher than with old vintages. In Bergman (1990) the "old" production units in steel or pulp and paper industries are assumed to have zero elasticities of substitution, whereas the elasticity of substitution of "new" production units in these industries is positive. In GREEN's dynamic structure, two kinds of capital goods coexit in each period, "old" capital installed in previous periods, and "new" capital resulting from current-period investment. This putty/semi-putty technology also implies different substitution possibilities by age of capital.

A more formal presentation of the aspect that the latest vintage, added to the aggregate capital stock, embodies innovation and technical improvement can be found in Conrad and Henseler-Unger (1986). The methodological approach is an integration of price-dependent input coefficients with input coefficients of the latest vintage, both derived from cost functions. The elasticity of substitution is the same for old and new vintages but the distribution parameters in the CES functions , that is the relative significance of the inputs, differ.

The integration of the „jelly“ capital concept with disembodied technical progress, used in the neoclassical approach to input-output analysis, with the vintage concept follows from adjusting, for example, an energy coefficient based on the new relative prices in $t + 1$ by the decay of old plants (d is the rate of decay) and by adding the input coefficient of the new plant or vintage:

$$(26) \qquad \frac{E_{t+1}}{X_{t+1}} = d_{E,t}^{s} \left(\frac{PE_{t+1}}{PX_{t+1}} \right)^{-s} (1-d) \; + \; (g+d) \cdot q_{E,t}^{s} \left(\frac{PE_{t}}{PX_{t}} \right)^{-s}$$

where $d_E\,(q_E)$ is the distribution parameter of the old (new) production process, and g is the growth rate of output.

The characteristic feature of this approach is that on the one side an input structure reacts to changes in relative prices by substitution on the basis of the jelly capital stock. On the other side, the input structure changes due to new energy-efficient plants (2. term in (26)) for the retired worn-out energy-intensive installations.[17] A similar approach of a vintage re-calibration has been used in the OECD model (Beghin et al. (1995)). At the beginning of each new period, the parameters of the production structure are modified to reflect the changing composition of capital.

A further methodological approach to take into account the vintage concept is to replace capital K in a restricted cost or profit function by Solow's (1959) expression for an effective capital stock. In his article, Solow criticized the disembodied nature of technical change in aggregate production functions. He emphasized the fact that most improvements in technology need to be embodied in net capital formation, or in the replacement of old-fashioned equipment, before they can be made effective. Solow proposed to distinguish capital equipment of different vintages and formulated a Cobb-Douglas function for output produced with capital of a given vintage. Technical change is represented by a rate of embodied technical change as well as of disembodied technical change. His measure of effective capital incorporates the assumption that all technical progress is embodied in the improving quality of successive vintages of capital investment.[18] If technical progress is unembodied in capital plant and equipment, then its effects do not depend in any way on the rate of investment in capital plant and equipment. An alternative notion is that technical progress is entirely embodied in the design and operating characteristics of new capital plant and equipment. According to this view, the energy saving effects of embodied technical progress depend critically on the rate at which new investment goods diffuse into the economy, i.e. on the vintage composition of the capital stock. For policy measures the nature of technical progress matters. If technical progress is embodied, tax credits for investments in new energy-efficient equipment provide an incentive to realize its effects more

[17] The adjustment of the distribution parameter d_E for energy in the CES cost function after the decay of retired vintages and the inclusion of new vintages is then $d_{E,t+1}^{s} = \frac{1}{1+g} \left\lfloor d_{E,t}^{s} (1-d) + (g+d) q_{E,t}^{s} \right\rfloor$.

[18] For a CGE application see Conrad and Ehrlich (1993).

quickly than if technical change were unembodied. However, under embodied technical change energy savings can be realized only by changing the energy using characteristics of the long-lived capital stock, whereas under unembodied technical change the effectiveness of the entire capital stock is augmented regardless of its vintage composition. One example of unembodied technical change is “learning by doing” in which workers learn how to produce more efficiently. However, if technical progress were embodied, it augments only the most recent vintage of investment, and not any of the earlier vintages of surviving capital.[19] Berndt et.al. (1993) have estimated the rates of embodied and disembodied technical change using a translog specification of a restricted cost function and data from the manufacturing sectors in the United States, Canada and France from 1970-1987. They found that embodiment played at best a modest role. From the total cumulative effects of technical progress, embodied technical progress was responsible for 0.5% in the U.S., 3.6% in Canada, and 10.7% in France. They conclude that technical progress embodied in new equipment is responsible for only a surprisingly small proportion of productivity growth.

Energy oriented CGE models introduce exogenously provided new technologies which are known but not yet implemented. These backstop technologies are already known today, but are options commercially of interest in the future. The introduction of these technologies depends on maturation (exogenous penetration time) as well as on the cost of production relative to competitive technologies. Backstop inputs are modeled to be available at an unlimited quantity for an exogenously given price. A precise knowledge of the technology in question is not necessary. For the design of carbon reduction policies Rutherford (1999) assumes that there exists a carbon backstop technology which can produce carbon-free energy at constant marginal cost. In simulations of carbon abatement policies costs of the carbon backstop are set equal to a future value per ton of carbon and then application of a carbon limit causes a gradual introduction of the backstop activity. The introduction of new alternative sources of fossil fuels depend on the exogenously given cost of the backstop.

The new generation of CGE models employ a more sophisticated treatment of endogenous technical progress by modeling explicitly the connection between R&D expenditure and knowledge growth. The models of Nordhaus (1999) and of Goulder and Schneider (1999) connect the rate of invention with resources spent on R&D. The Nordhaus-model of induced innovation describes the impact of changes in prices or regulation on the innovations in different sectors. At a given time, there is an existing stock of general and sector-specific basic knowledge and engineering knowledge. Resources (research as an input) can be applied to improve the state

[19] For the definition of the capital stock in efficiency units see Solow (1959) and Berndt et al. (1993).

of knowledge (called "innovation") in order to raise the productivity of resources. The conclusion of the study based on the DICE model (Nordhaus (1992, 1994)) was that induced innovation seems to be a less powerful factor in implementing climate-change policies than substitution. The reductions in CO_2 concentrations and in global mean temperature due to induced innovation turned out to be approximately one-half of those due to substitution. Goulder and Schneider (1999) model induced technical change in greenhouse gas abatement by making R&D for lower-carbon technologies responsive to the economic incentives created by greenhouse gas policies. Firms employ labor, capital and two types of energy and materials to produce output. By distinguishing conventional (carbon-based) energy from alternative forms of energy, they can consider how a tax on carbon influences incentives to R&D in alternative fuels industries. And by distinguishing carbon-intensive materials from other materials, they can observe how the performance of other industries might depend on the extent to which carbon fuels are a significant input into production. In addition, they distinguish physical capital and knowledge capital. The former is expanded by investment in new physical capital, the latter by expenditure on R&D activities. Enlarging either capital stock raises the productivity of energy and non-energy inputs.[20] They apply the model to the US economy but concede that it is (not yet) possible to obtain precise data on the technology for producing R&D services or to identify precisely the relationship between R&D services and knowledge capital. These new models are inspired by the industrial organization literature or by macro models of induced technological change (Romer (1990)). A CGE application of these approaches needs calibration of parameters which express the strength of substitution possibilities between knowledge capital and ordinary inputs or the spillover knowledge enjoyed by all industries. More econometric studies need to be carried out in order to provide an empirical background for the calibration of R&D related parameters.

9. Abatement Technologies

If emission data are directly associated with the volume of output, that is abatement activities are not endogenously modeled, then the only way to reduce emissions is by reducing output. This is a rather unpleasant conclusion for countries troubled with unemployment as well as

[20] For an extension of this model with two channels for knowledge accumulation (R&D and learning by doing) see Goulder and Mathai (2000). In this model a social planner chooses optimal paths of carbon abatement and carbon taxes taking into account the impact of taxes on technological progress and future abatement costs. The stock of technological knowledge enters the production function and, at the same time, affects the emission output ratio.

for developing countries. However, for an analysis of the impact of environmental regulation on international competitiveness and on growth, the inclusion of the operating costs of pollution control is of importance. Polluting firms can react to standards and/or emission taxes either by factor substitution or by abatement activities or by both. They have abatement cost functions and determine the level of the abatement activity by equating marginal cost of abatement to the uniform tax rate on emissions. Abatement activities also imply demand for intermediate goods, for capital and for labor. Depending on the objective of the study, several approaches to impose pollution control regulations on the technology can be found in the literature. The easiest way to deal with the problem of how to model abatement technologies, is to study the economic impact of reducing carbon dioxide emissions. Since there are no carbon abatement technologies available at reasonable economic costs, this explains the popularity of modeling CO_2 reduction policies. Substitution and output effects are the only measures to reduce CO_2 emissions.

In determining the impact of environmental restrictions on economic growth, Jorgenson and Wilcoxen (1990) simulated U.S. economic growth with and without pollution control in effect. For eliminating the operating cost of pollution control for constructing their base case, they estimated the share of pollution abatement in total costs of each industry to compute the share λ_i of costs, pollution abatement excluded, in total costs. To simulate the effect of eliminating the operating costs associated with pollution controls for all industries, they insert the cost shares λ_i into the unit cost functions for these industries, i.e.

$$\ln p_i = \ln \lambda_i + \ln c_i \, (w, t) \, .$$

To simulate the impact of eliminating controls on motor vehicle emissions they reduced the price of motor vehicles in proportion to the cost of pollution control devices. Finally mandated investment in pollution control equipment has been implemented as an increase in the price of investment goods.

Hazilla and Kopp (1990) impose pollution control regulations also directly on the technologies. They model their impact through modification of the derived input demand equations in each sector. The input structure of each industry is modified to account for increased input usage required by regulation. In Bergman (1990) total emissions of air pollutants (SO_2, NO_x, CO_2) can be reduced by means of separate cleaning activities that are available to all sectors. Technically the reduction of emissions is modeled as a central abatement unit, selling services to the different sectors. The price of these abatement services is equal to marginal cost of abatement This price then will be determined on the market for emission permits implying that marginal cost of abatement will be equal across sources of emissions.

In Conrad and Schröder (1991a, 1993) and in the GEM-E3 model (Capros et al. 1996) abatement activities are modeled such as to increase the user cost of the polluting inputs in terms of additional operating costs. Let d be a degree of abatement which is defined as the ratio of abated emission over potential emissions ($0 \le d \le 1$) and $c(d)$ are the cost of abatement measures per unit of emission or waste, measured in base year prices. They depend on the degree of abatement with $c'(d) > 0$ and $c''(d) > 0$. Then the user cost of fossil fuel, for instance, is $\tilde{w}_F = w_F + w_M \cdot c(d) \cdot d \cdot e$ where w_F is the fuel price, w_M is the price of material or abatement technology and e is an emission or waste coefficient in terms of tons of an air pollutant per unit of energy input. User costs therefore consist of the fuel price w_F and of the additional costs due to environmental regulation when using one unit of the fuel input. This user cost of energy increases over-proportionally with an enforcement in environmental regulation.[21] On the production side this implies an increasing share of complementary material inputs. The change of the user cost of energy will also cause the firm to alter its input choices. A stricter environmental policy will have a substitution effect which will result in a reduced demand for energy and its price complements and in an increased use of its substitutes. This integration of abatement costs in a user cost concept can be used to model the impact of regulation on household and firm behavior; for the latter each sector should be treated separately.

The user cost approach can be extended to the case of several pollutants, either air pollutants, water pollutants, or land pollutants. Furthermore, if there is a tax on a pollutant, then there is also a cost component for the emissions released, i.e.

$$\tilde{w}_F = w_F + w_M \cdot c(d) \cdot d \cdot e + t(1 - d) \cdot e.$$

Finally, if there is an energy tax and / or an emission tax on carbon dioxide, t_{CO}, where no convenient end-of-pipe measures exist, then d is equal to zero in this user cost of fuel.

This approach permits to model the effect of alternative environmental policies. If there is a regulated degree of abatement, then users of furnaces have to adhere to governmentally enforced limits of emissions which can be interpreted as a minimum degree of abatement $\bar{d}$. Then the degree of abatement is given and abatement costs increase the price of energy. If a tax on emission is introduced, the degree d is a decision variable of the firm.

[21] With $C(d) = c(d) \cdot d$, then $C'' = c''(d)d + 2c'(d) > 0$.

Cost minimization with respect to the degree of abatement *d* yields the optimal degree.

Furthermore, future environmental regulations can be accounted for by modifying the emission coefficients for appropriate sectors. For instance, as new cars are equipped with catalytic converters, the emission of NO_X for a given amount of gasoline will fall gradually (see Glomsrod et al., 1992; Conrad and Schröder, 1991a).

In the user cost approach environmental regulation will have an impact on the composition of the energy aggregate, it will increase the price of the product produced with fuel, and it will reduce the demand for energy.

10. Data Requirements

The source of data for the multi-sectoral CGE models are the national accounts and input-output tables which can be comfortably combined in the framework of the Social Accounting Matrix (SAM). If yearly input output tables are available, then the parameters of the unit cost functions and of the factor demand functions can be estimated econometrically (e.g. Hudson and Jorgenson (1974) and Jorgenson and Wilcoxen (1990a, b). The econometric approach is very demanding in terms of data requirements but makes it possible to incorporate behavioral responses to changes in relative prices based on the behavior in the past. However, given the often poor data situation (the latest input-output table is often 5 years old), and the high degree of aggregation, the knowledge of an estimated elasticity of substitution between energy and capital or energy and material in the investment goods industry might not be worth the enormous effort required to explore the production structure from a set of yearly input output tables. The common approach in CGE modeling is therefore to choose nested CES functional specifications which account for different degrees of substitutability between input factors on different nesting levels. The distribution parameters which indicate the relative significance of the inputs are calibrated (calculated) from benchmark data, but the substitution elasticities have to be taken from other sources. A typical source are substitution elasticities presented in the econometric literature or own "best-guess" estimates. Since sign and magnitude of those estimated elasticities differ, some model builders assume capital and energy to be complements and labor and energy to be weak substitutes. Those CGE modelers, who assume energy and capital to be substitutes rather than complements face the problem that the adjustment to new relative prices will be complete and immediate. As the demand for energy reflects to a significant degree the properties of the existing stock of capital, this is hardly a satisfactory assumption. A reasonable alternative to the question about the true elasticity of substitution is to carry out different simulation studies. What we know is that a high degree of substitution among inputs implies that the cost of environmental regulation is low, while a low degree of substitutability implies higher costs of environmental regulation. The higher the substitution elasticity between labor and energy, the higher the chance that an ecological tax reform, which taxes energy and reduces non-wage labor cost, will raise employment. If we simulate the nature of substitutability among inputs by assuming a CES specification both with a low elasticity of substitution, and then with a higher one, we get an interval for the range of economic effects from an environmental policy. This is maybe more informative than getting a point-forecast under the econometric approach.

The response of an economy to changes in environmental regulation depends also crucially on assumptions made with respect to which variables are exogenous and what is their magnitude then. A standard assumption is exogenous technical change or population growth. In most models the price of crude oil is exogenous as is the foreign exchange rate. It is not always desirable to endogenise each economic variable (e.g. the exchange rate), because this makes it harder to understand the outcome of a policy simulation due to the huge number of potential channels.

11. Environmentally Related Simulation Analyses Using CGE Models

11.1 The Double Dividend Policy

CGE analyses have played a key role in the evaluation of green tax reforms, the reorienting of the tax system to concentrate taxes more on "bads" like pollution and less on "goods" like labor input or capital formation. Before turning to an example of a double dividend analysis[22], it is useful to comment on how the incidence of a tax reform should be measured. It can be assessed by looking at the equivalent variation *(EV)* associated with the tax change for each participant in the economy. The *EV* provides a dollar measure of the impact of a given tax change on individual economic welfare. The *EV* gives the change in expenditure at base prices P^0 that would be equivalent to the policy implied change in utility. The *EV* may be computed as follows:

[22] For a state-of-the art review on the double dividend issue see Goulder (1997) and Bovenberg and Goulder (2001).

(27) $$EV = e(P^0, U^1) - e(P^0, U^0)$$

where $e(\cdot)$ is the expenditure function which depends on the consumer price vector P^0, and initial utility U^0 or post tax utility U^1. If $EV < 0$, welfare after the policy measure is lower than in the base case. The consumer is willing to pay the maximum amount EV at the fixed budget level $e^0 = e(P^0, U^0)$ to avoid the decline of utility from U^0 to U^1. Similarly, if $EV > 0$, the consumer would be willing to pay the maximum amount EV to see the change in environmental policy implemented. Alternatively, similar measures such as the compensating variation *(CV)* that replaces P^0 in (27) with the tax reform price vector given the initial utility level U^0, may be used in assessing tax reforms.

The question in the double dividend debate is whether the internalization of environmental externalities can be beneficial for other policy areas as well since the revenues from pollution taxes could be used to cut other distortionary taxes. The non-environmental dividend can be defined in various ways. Given the important unemployment problem in the EU, priority has been given to the analysis of distortions in the labor market that might explain persisting unemployment.[23] The revenue from the pollution taxes are recycled to cut labor taxes. On the one side, the narrow base of an energy tax constitutes an inherent efficiency handicap. On the other side, the impact of the tax reform on pre-existing inefficiencies in taxing labor could offset this handicap and a double dividend arises. Therefore, in principle a double dividend can arise only if (i) the pre-existing tax system is significantly inefficient on non-environmental grounds and (ii) the revenue-neutral reform significantly reduces this prior inefficiency. The double dividend actually arises only if the second condition operates with sufficient force. However, it could also arise if the burden of the environmental tax falls mainly on the undertaxed factor (e.g. immobile capital) and relieves the burden of the overtaxed factor labor.[24]

As an example of such a policy analysis we present results from the GEM-E3 project (Capros et al. (1996) or Conrad and Schmidt (1998)). In that model CO_2 emissions have been reduced by 10 percent in each country in the base year (the non-coordinated policy approach). For that purpose a CO_2 tax with a rate just high enough to achieve the 10 percent reduction in each country has been introduced. The revenue from this tax was used to reduce the contribution to social security by the employers. The carbon tax should affect the substitution

[23] For theoretical papers on the double dividend issue see Bovenberg and Goulder (1996); Goulder (1995). For empirical papers see Jorgenson and Wilcoxen (1992), Proost and van Regemorter (1995) and Welsch (1996).
[24] See Bovenberg and Goulder (2001) on this point.

of other inputs for energy and contributes therefore to reducing global warming (first dividend).[25] This substitution effect could have a positive impact on the demand for labor if output would remain on the pre-reform level. However, the recycling of the tax money to social insurance as a partial compensation for employers' contribution could definitely increase the demand for labor (second dividend). The hope by the advocates of the double dividend is that the substitution effect of labor for energy outweighs the negative output effect resulting from lower growth when the tax is imposed.

The model considers full competitive equilibrium in all markets, including the labor market. We have included leisure of only employed persons in our welfare measure *EV*. If a policy simulation results in more leisure, this is interpreted to be equivalent to an increase in the number of employed persons. We will use the double dividend terminology for policies resulting in less CO_2 emissions and in more employment irrespective of whether consumption has declined due to lower real wages. In principle, there could be a third dividend, because $EV > 0$ can imply more leisure (of newly employed persons) as well as more consumption in addition to a better environment. It can also imply less consumption dominated by more leisure, or less leisure dominated by more consumption. The first column of Table 1 shows the equivalent variations in ECU per capita. Since all signs are positive and the burden on the environment is reduced by 10%, there is a double dividend effect for all countries. A German, e.g., is willing to pay at most 62 ECU to see such a policy to be implemented. The EV per capita is the highest for Denmark and The Netherlands and the lowest for Greece.[26]

The figures in column 2 show negative growth rates for gross domestic production. Since employment, in turn, increases (see column 4), labor productivity declines. If in addition to employment (that is leisure) consumption increases, EV will be positive in any case according to the formula for EV. Italy and Greece with the lowest increase in real wages show a negative change in consumption. In these two countries the reduced purchasing power from higher energy prices can not be compensated by the increase in real wages. As leisure of employed persons enters our utility function, the growth in employment explains their positive EV. As investment declines (not shown in the table) for all countries but Belgium, the double dividend policy is not a strategy for more growth in capital formation. Also not shown in the table are the negative changes in exports and imports.

[25] This dividend can not be quantified by our model because our utility function underlying the EV (see section 5) does not include the amenities from the environment.
[26] Favorable recycling results are also obtained by Jorgenson and Wilcoxen (1992). Recycling fails in Bovenberg and Goulder (1997), Goulder (1995) and in Proost and van Regemorter (1995).

The growth in employment differs by country due to different CO_2 tax revenues. Countries with a high CO_2 tax rate have also high growth rates in employment (e.g., Denmark and the UK), because a higher tax revenue can be used to reduce the cost of labor. Substitution of labor for energy, given the price of labor and the higher price of energy, induces more employment. But especially the lower cost of labor from the relief in non-wage labor cost enhances the substitution of labor for other inputs. Due to changes in relative output prices, output of industries where energy is a minor input will increase and output of energy intensive industries will decline. This leads to an intersectoral mobility of labor from industries hit by CO2 tax to industries which benefit from relative output change and reduction in non-wage labor cost. The negative output effect from lower production cannot offset the positive effects from substitution. This kind of argument explains why Italy with the second highest CO_2 tax (33.75) has only moderate growth in employment (0.34%); its production declines by more (-0.43%) than the average rate in the EU (-0.36%). However, as we model a flexible wage rate, higher demand for labor will, in turn, increase the wage rate. A higher real wage rate will then partly offset the double dividend policy of reducing the cost of labor. The positive growth effect of a higher real wage rate on private consumption may, however, offset partly the labor cost effect. Column 6 finally shows an average tax rate of 23.51 per ton of CO_2 and a group of countries with a lower rate (e.g., Belgium or Greece) and a group with a higher rate (e.g., Denmark or Italy). The tax rate depends on country-specific emission coefficients, on the energy intensity, on the energy mix, and on the cost of avoiding CO_2, i.e., the elasticities of substitution.

As for a global pollutant marginal damage is about the same for each country, for efficiency reasons the tax rate should be the same. We therefore have lowered overall CO_2 emissions of all EU member states by 10 percent, irrespective of the source of CO_2 (the coordinated policy approach). In order to achieve this bubble concept, we have calculated a EU-wide CO_2 tax rate such that its level will guarantee the reduction of total EU-CO_2 emissions by 10 percent. Again each country will collect the tax revenues from its domestic firms and will use the money to lower employers' contribution to the social security insurance. We expect that the CO_2 tax rate under the bubble concept will be somewhat lower than the average of the rates under an uncoordinated, country by country CO_2 policy. Because of the cost-effectiveness of a coordinated policy we also expect that the tax revenue from the CO_2 tax under the coordinated policy will be lower than the sum of the revenues collected under the single country policy. The reasons for the national differences in the impacts of a CO_2 policy are the different structure of the economies in terms of different weights of the energy intensive industries, of the service sector, of the composition of exports and imports or the difference in equipment with consumer durables. All these factors imply a different slope of the marginal cost curve of avoiding CO_2.

We next turn to the results obtained under the coordinated carbon reduction policy. In this case there is a uniform tax rate whereby the countries' contributions to the CO_2 reduction target of ten percent for the EU can differ. Efficiency of this policy shows up in the lower overall tax rate of 21.8 ECU/ton CO_2 compared to 23.5 ECU/ton CO_2 as the average rate under the coordinated policy. As production declines somewhat less (-0.35) than under the non-coordinated policy (-0.36), a lower level of production can not be an explanation for the lower tax rate. The labor market dividend is somewhat reduced under a coordinated policy because tax revenues are lower. Less leisure and somewhat less consumption explain why the EV for the EU is lower under a coordinated policy. Although the overall performance for the EU does not change very much, for some countries a coordinated CO_2 policy matters. The labor force in countries with a low CO_2 tax under the non-coordinated policy like Belgium and Greece is pleased to have a higher uniform CO_2 tax. The additional revenue of this tax supports the labor market dividend. The labor force in countries with a high CO_2 tax under the non-coordinated policy are in turn not so fond of the coordinated policy. For Italy, e.g., employment now increases by only 0.23% compared to 0.34 under the non-coordinated policy.

Another measure of efficiency is labor productivity. The change in output minus the change in labor input is –0.75 under the coordinated policy and –0.80 under the non-coordinated policy; i.e. labor productivity declines more under the non-coordinated policy. However, all those efficiency arguments are buried by the welfare effect of more employment and a higher real wage rate, and hence of more leisure from persons now being employed, and of more consumption.

Our numerical results indicate that the beneficial efficiency impact from the reduction of pre-existing inefficiencies in taxing labor in the EU seems to be large enough to overcome the efficiency handicap of the narrow tax base of the CO_2 tax. However, our findings can also be linked to the factor mobility assumption made in the GEM-E3 model. The putty-clay approach used in this recursively dynamic model is based on the assumption that sectoral capital stocks are fixed within a single period. In such a situation the burden of the environmental tax falls partly on capital as stocks can adjust only gradually over time by depreciation and gross investment. Another explanation for the double dividend outcome can be the foreign trade specification and its parameterization (elasticities of substitution in the Armington function).[27]

11.2 Global warming and the cost of greenhouse gas emissions control

Most efforts to study energy-economy-environment interactions using (multi-regional) CGE models address the problem of global warming. Examples in this field are the Nordhaus-models DICE (Nordhaus, 1992), the Global 2100 model of Manne and Richels (1990, 1992), the MERGE model of Manne et al. (1995), the OECD model GREEN of Burniaux et al. (1992), the model G-CUBED of McKibbin and Wilcoxen (1992), the LEAN model by Welsch and Hoster (1995), and the EU-model GEM-E3 (Capros et al., 1996).[28] Since space does not permit to describe all the features of these models, we will make only some short comments. The GEM-E3 model (Capros et al., 1996; Conrad and Schmidt 1998a, b) is based on a disaggregated representation (11 industries) of 14 EU member state economies linked by trade flow matrices for each of the eleven goods considered. The model addresses to problems of global warming and of acidification. Emissions of pollutants CO_2, SO_2 and NO_X are differentiated by country, sector of origin, type of fuel, and by goods (producers and consumers durable goods, and non-durable goods). A variety of policy instruments are used to affect transboundary air pollution, deposition, additive (end-of-pipe) and integrated (substitution) abatement.

Recent CGE models address the importance of international trade and financial flows in evaluating greenhouse gas (GHG) control costs. The topic is crucial to understand GHG control costs not just because international trade and financial linkages are important, but also because the 1997 Kyoto Protocol would require different proportionate emission control efforts by the industrialized countries and no controls at all by developing countries. McKibbin et al. (1999) use an econometrically estimated multi-region, multi-sector CGE model of the world economy to examine the effects of using a system of internationally tradable emissions permits to control CO_2 emissions. Their results show that international trade and capital flows significantly alter projections of the domestic effects of emissions mitigation policy, compared with analyses that ignore international capital flows. Since the US has relatively low GHG abatement costs within the OECD, it could be even a net supplier of permits. Bernstein et al. (1999) also find significant

[27] A detailed discussion on why GEM-E3 produces a double dividend is given in Conrad and Schmidt (1999).
[28] For a more detailed summary of models for studying environmental policy effects see Jorgenson and Wilcoxen (1993).

aggregate gains from international emission trading, with winners and losers depending on the nature of the trading regime (i.e., only industrialized countries vs. a global system involving China and India as well). Their CGE world model focus on the international trade aspects of climate change policy which include the distribution of impacts on economic welfare, international trade and investment across regions, the spillover effects of carbon emission limits and the effect of international emission trading.

In principle, CGE models could also be used to study optimal GHG policies under the possibility of an irreversible global catastrophe. As temperature increases up to a threshold value, marginal damage increases sharply. The type of models which analyses possible catastrophic outcomes arising from global warming are small theoretical or numerical models where a catastrophic event is assumed to reduce the utility of consumption (or production).[29] Since precise knowledge and empirical evidence on catastrophic occurrences are lacking, there is no need to employ a full-scale CGE model.

11.3 Environmental regulation and economic growth

Environmental regulation affects the supply side (marginal costs) and the demand side (abatement expenditure). In assessing the impact of environmental regulations on growth; Jorgenson and Wilcoxen (1990a) modify their basic model which implicitly includes environmental regulation in the 1970's and early 1980's, because it is based on historical data. Thus, to determine the effect of regulation on the performance of the US economy, they conduct counterfactual simulations in which regulation is removed. They found that the long-run cost of regulation is a reduction of 2.6 percent in the level of the U.S. gross national product during the period 1973-1985. Over this period the annual growth rate of the U.S. economy has been reduced by 0.19 percent. Since the stringency of pollution control differs substantially among industries, their model also assesses the impact of environmental regulation on individual industries. For example, they find that the long-run output of the automobile industry has been reduced by fifteen percent, mainly as a consequence of motor vehicle emissions controls.

[29] See Gjerde, Grepperud and Kverndokk (1999) for such a model.

11.4 Tradable permits for CO_2

When permits for air pollutants are introduced, then the supply of permits is exogenous and the endogenous permit price equilibrates demand and the fixed supply. Whereas for taxes the recycling of revenues is an important issue, for permits it is not because the initial endowment is based on the grandfathering principle and not on auctioning the permits. For reasons of cost-effectiveness, a permit system for the European Union should be introduced and not separate non-coordinated, country-specific systems in order to curb global CO_2 emissions. Such a topic was pursued in Conrad and Schmidt (1998a, b, c). Major interest of the analysis was laid on the national and EU-wide economic impacts of such a policy. In the non-coordinated case each country reduces ten percent of its base line CO_2 emissions: the permits are traded between sectors and households within the country. In the coordinated policy, the permits are traded between all European sectors and households to realize a ten percent reduction of the EU's total CO_2 emissions. Curbing SO_2 emissions by introducing coordinated or non-coordinated pollution permit systems is also of interest. An EU-wide permit system for the electricity sector that is operational and in line with the requirements of the Oslo Protocol (convention of Transboundary Air Pollution) was introduced and national and EU-wide economic impacts were studied.

11.5 The costs of environmental standards

Although most countries use technical standards to curb air pollutants, modeling the effect of market-based instruments is very popular among CGE model builders because they favor allocation through relative prices. The command-and-control approach can be based on technical restrictions, on concentration of an emission or on the use of an input. They affect the technology and hence the cost of production. A different CGE application is to measure the inefficiency of the present regulation by air quality standards by introducing taxes which warrant the same air quality (Conrad and Schröder, 1993). For measuring the cost effectiveness of such a change in environmental policy, first a base run is produced based on present emission standards, given by the air quality acts. These emission standards can be converted into permitted emissions per unit of input. Emissions considered are SO_2, NO_X and particulates. Simulations then show the economic impact of an efficient environmental policy in which all industries are confronted with uniform emission tax rates which have been computed such as to guarantee exactly the air quality under the base run with standards. This minimizes abatement costs given the quality of the air from the base run. The result was that real GNP in 1996 would have been higher by 0.6

percent and unemployment lower by 14 percent if emission taxes instead of standards had been introduced in 1988. In Goulder et al. (1999) a simple CGE model is used to compare the costs of command-and-control and incentive-based environmental policy instruments in the presence and absence of distortionary taxes.

11.6 Forestation and deforestation

As the forest is a carbon sink if it absorbs more carbon than it releases through felling and natural decay, implementing the forests as carbon sinks in a CGE model is another topic. Persson and Munasinghe (1995) simulate the effect of government policies on Costa Rican forests to reduce deforestation. The allocation of property rights to forests results in a dramatic decrease in deforestation and an increase in the net import of logs. Activity in the forest sector increases significantly because of the increase in imports of logs. Forests are multiple – use assets because if forest is used as a carbon sink, it cannot be used as a raw material in the pulp and paper industry. CGE models can evaluate the efficient use of forests as an intertemporal allocation problem (Pohjola (1996)).

11.7 Environmental policies for developing countries

CGE models for developing economies can be used to analyze the links between growth and environment and between trade policies and the environment. Of special interest are efficient economic policies which can readily be implemented in the context of a developing country. At the OECD Development Centre CGE models for three Latin America economies (Chile, Costa Rica, Mexico), and three Asia Pacific economies (China, Indonesia, Viet Nam) have been developed to shed light on the importance of these links, or on the main mechanisms through which changes in trade regimes have impact on the environment (Dessus, Roland-Holst and van der Mensbrugge (1996)). In international trade, for example, countries with less stringent environmental regulations may have comparative advantage in dirty industries. This leads to the export of "pollution services" embodied in goods made with technologies that do not meet the environmental standards of the importing countries. Using a CGE model for Indonesia, Lee and Roland – Holst (1997) show that a combination of trade liberalization and a cost-effective tax policy would not only raise the country's welfare, but it can also improve the environmental quality. Their results indicate that unilateral trade liberalization by Indonesia would increase the ratio of emission levels to real output for almost all major pollution categories. When tariff removal is combined with a cost-effective tax policy, then however the twin objectives of welfare enhancement and environmental quality improvement appear to be feasible. CGE models have also been used to project the effects of trade liberalization on the economy and the environment concentrating especially on the issues of fertilizers and transportation or on tropical deforestation. Beghin et al. (1995) combine environmental and trade policies for Mexico and show how they interact.[30] Contrary to the common fear, economic integration of Mexico in the regional economy will not exacerbate environmental degradation. The pollution elasticity with respect to growth is very stable in Mexico (near unity) and trade orientation does not have much impact on the elasticity.

Interaction between environmental policies and trade policies is of interest not only for developing countries but also for Eastern European countries which are going to join the European Union. For these countries environmental regulations equivalent to those already introduced in the EU may affect their competitiveness and patterns of trade. The approach to measure these effects could follow Ho and Jorgenson (1998), who examined the impact of environmental regulations enacted in the 1960s and 1970s by projecting the evolution of the U.S. economy with and without these regulations. Their approach consists of first running a base-case simulation designed to mimic the actual evolution of the U.S. economy. The base case simulation is a regime with pollution controls mandated by the environmental laws in place. To assess the impact of the controls, they perform counterfactual simulations where they are removed. That is, they calculate the path of the economy, including how the sectors evolve and how the trade pattern change, had there been no environmental regulation in the U.S. before 1980. For the Eastern European countries the base case simulation could be a regime with lax pollution controls.

11.8 Joint implementation

International treaties on climate protection allow, in addition to domestic actions, for the supplementary use of flexible instruments in order to exploit cheaper emission reduction possibilities elsewhere. One concrete option for industrialized countries would be to enter joint implementation with developing countries such as India or China where the industrialized country pays emission reduction abroad rather than meeting ist reduction target solely by domestic action. Joint implementation allows for the reduction of domestic emission

[30] See Steininger (1999) for a survey on general models to analyze international trade aspects under environmental regulation.

taxes without adverse effects on the environmental dividend. In addition, joint implementation is typically based on technology transfer where the host demands investment goods by the donor triggering direct positive employment effects for the latter. Based on CGE models for Germany and India, Boehringer et al. (2000) compare employment and welfare effects under a revenue-neutral environmental tax reform versus a tax reform cum joint implementation. The open question was whether an environmental tax reform in Germany combined with joint implementation in the Indian electricity sector could improve the prospect for a double dividend: Not only that joint implementation would lower the level of emission taxes in Germany and thus reduces adverse effects on labor demand; but also investment demand for energy efficient power plants produced in Germany would trigger positive employment effects in the German manufacturing industries. From the Indian perspective, joint implementation would equip its electricity industry with additional capital goods leading to a more efficient power production with lower electricity prices for the economy. In their model analysis, revenue neutral carbon taxes have a negative impact on employment in Germany, however joint implementation can help to diminish this effect through the associated cost savings and additional investment demand from joint implementation with host countries.

11.9 Environmental policy in agriculture

Issues like agricultural chemicals, food safety and water quality have brought agriculture and nonpoint source pollution to the forefront of environmental attention. Significant crop yield increases over the last several decades have been associated with the adoption of pesticides and fertilizers. At the same time, agriculture chemicals may impose economic costs on the environment and human health. Using a CGE model of the US economy, Hrubovcak et al. (1990) weigh such tradeoffs for assessing the benefits and costs from integrating agricultural, environmental, and food safety policies. They found that public policies designed to simultaneously satisfy farm income and environmental objectives face some serious challenges. Efforts to achieve a reduction in agricultural chemical use through taxes should impact chemical use and reduce environmental residuals. But output price and production uncertainties, coupled with uncertainties about the elasticities of substitution between key inputs, generate significant uncertainties on the beneficial environmental impacts.

12. CGE models with a two-way link between the environment and the economy

Many environmentally related CGE models take into account that emissions and the accumulation of pollutants negatively affect the quality of the environment. In those models there is a one-way link between the development of economic variables and their generation of environmental externalities (Glomsrod et al. (1992), Ballard and Medema (1993), Boyd et al. (1995) or Brendemoen and Vennemo (1996)). However, the quality of the environment has also an impact on the performance of economic variables. Models with a two-way link include in their simulation studies environmental feedbacks on labor productivity, capital depreciation and on the welfare of the consumer. Noise, traffic accidents and reduced air quality affect the welfare of the consumer as well as his labor productivity. Capital depreciation is negatively affected by the increase in corrosion caused by sulfur emissions or infrastructure capital by heavy traffic. Acidification of forests leads to decreased growth in forests and reduced recreational value. The objective of these studies is to develop a measure of green net national product and to show that growth in GDP or consumption is not equivalent to growth in welfare because of the effect of deterioration of the environment on welfare. CGE models which include the two-way link have been developed by Nordhaus (1994), Vennemo (1997), or Bergman and Hill (2000). In Nordhaus, the accumulation of CO_2 emissions increases the temperature of the earth which harms production. In Vennemo's DREAM model external effects of economic activity are evaluated in terms of their costs on the economy. Damage estimates have been produced for acidification of lakes and of forests, for health and annoyance from emissions of NO_x, SO_2, CO and particulates, for corrosion, noise, traffic accidents, congestion and road depreciation. In his simulation experiment he finds that the feedback on environmental quality is much more significant for consumer welfare than the feedback in the form of increased depreciation and a decline in productivity. Bergman and Hill model productivity effects of environmental stock and flow pollution by including damage effects from pollution accumulation on production. To model the feedback effects, the resource endowments are included in the model and the externality is linked to these endowments. The model assesses the effects that the inclusion of feedback mechanisms and the use of defensive expenditure might have on GDP and on consumption. It turns out that the positive productivity effects of proposed emission reductions are smaller than the costs of attaining these emission reductions. The feedback of traffic and congestion on economic variables is another externality related aspect which has been modeled by Conrad and Heng (2000) using a CGE model for Germany. In a baseline scenario it is shown how congestion and its costs will develop over time given the present bottlenecks in road infrastructure. The present stock of trucks and private cars deviates from the capacity related stocks which results in a congestion index. This index affects the efficiency of firm-owned trucks and of trucks owned by the transportation industry. The reduced efficiency raises the cost of transportation in the economy due to costs of the substitutes for truck transportation and labor cost paid during congestions. Congestion, due to the unsufficient provision of infrastructure, and the negative externality effect from the growth in truck transportation raises the prices in the economy and generates a non-optimal allocation of resources. Given the necessity to act the fuel tax is raised in the model to partly finance infrastructure investment. The cost of the addition in infrastructure are then compared with the savings in congestion costs in order to see whether such a policy measure is self-financing. It turned out that the savings in congestion costs exceeds by 50 percent the costs of the addition in infrastructure investment.

The specifications chosen by the authors are very pragmatic and some features are given next.

Nordhaus:

Environmental feedback on output *X* with *D* as the loss in output is

$$\frac{D(t)}{X(t)} = q_1 \cdot T(t)^{q_2}$$

where *T* is temperature change and q_1, q_2 are parameters. Abatement costs *TC* are:

$$\frac{TC(t)}{X(t)} = b_1\ m(t)^{b_2}$$

where m is the degree of abatement and b_1, b_2 are parameters. Combining the loss in output and cost relationships, a feedback relationship Ω of global warming on productivity can be derived:

$$\Omega(t) = \frac{\left(1 - b_1 m(t)^{b_2}\right)}{\left[1 + q_1\ T(t)^{q_2}\right]}$$

It comprises damage and cost effects in one term and enters a production function

$$X(t) = \Omega(t) \cdot A(t) \cdot K(t)^{g} \cdot L(t)^{1-g}$$

Vennemo:

There is a health induced productivity index h:

$$h = h(F) \quad , \qquad h' < 0$$

where F is fuel oil consumption.

A capital depreciation rate s also depends on fuel consumption:

$$s = s(F) \quad , \qquad s'(F) > 0 .$$

An index of intertemporal utility U captures the two-way link:

$$U = \frac{P_0}{P}\left(W_{-1} - D\right) + D_0$$

where $P(P_0)$ is an intertemporal price index of wealth (baseline scenario), W_{-1} is household wealth and $D(D_0)$ is value of negative externalities (baseline scenario).

Bergman and Hill:

A link between the accumulated sulfur and nitrogen stock, S, and the forest endowment is expressed as:

$$NR_t = f_t(S_t) \cdot NR_{0,t}$$

where f_t is a linear function of the stocks and NR_t is the actual annual harvest from the forest resource at time t ($NR_{0,t}$ is the path from the baseline scenario).

Feedback on labor productivity is modeled as:

$$L_t^{Tot} = \bar{L} - g^{NO_x} \cdot \left(F_t^{NO_x} - \bar{F}^{NO_x} \right) \cdot L_{0,t}^{Tot}$$

where L_t^{Tot} is aggregate efficient labor endowment at time t and $L_{0,t}^{Tot}$ is the baseline scenario path. $\bar{F}_t^{NO_x}$ is the pollution flow level of the pollutant below which there is no negative impact on aggregate labor productivity, and $F_t^{NO_x}$ the simulated pollution flow level ($\bar{L}$ is unadjusted labor endowment and g^{NO_X} is a positive parameter chosen in the calibration process).

Conrad and Heng

The stock of transportation equipment by n firms and private households $(n+1)$ affects an index Z of congestion:

$$Z = \exp\left(\frac{a}{KI^*} \right) \prod_{k=1}^{n+1} \left(\frac{KT_k^0}{\bar{KT}_k^0} \right)^{b_k} \qquad , \qquad a > 0 .$$

KI^* is an optimal provision of infrastructure which minimizes transportation costs in the economy subject to a financial constraint. The exponential term measure the shortage in infrastructure capacity and converges to one from above if $KI \rightarrow \infty$. KT_k^0 is the stock of transportation capital in industry k and $\bar{KT}_k^0$ is the lower stock related to the present quality and quantity of the infrastructure network. The parameter b_k measure the contribution of trucks in industry k to the congestion externality which affects the cost of production of each industry. Each industry has transportation costs CT in its nested input structure which are expressed as a short-run, variable sub-cost function

$$CT = CT(T, PT_1, PT_2, PT_3, KT^e)$$

where PT_i are the prices of the substitutes for transport services from firm-owned trucks (i = 1: road transportation, i = 2: water ways, i = 3: railways). T is the transport volume and KT^e is the quasi-fixed transportation capital input in terms of firm-owned trucks defined as

$$KT^e = KT(KT^0, KI) \cdot Z^e$$

where $e < 0$ is the elasticity of effective transportation capital with respect to the index of congestion, *Z*. Infrastructure *KI* affects the utilization of the stock KT^0 and reduces congestion. Partial derivative of the cost function with respect to KT^0 measures as an ex-post or shadow price of capital the benefit of having one more unit of the stock KT^0. It expresses the savings in the variable cost of transportation by having one additional truck given the transportation volume *T*. Using this price, congestion costs caused by each industry can be calculated which then could be reduced by investing in infrastructure.

13. Limitations of CGE Models and Outlook of Future Research

Given the challenge to more restrictive environmental regulation in the near future, it is becoming more and more important to quantify the costs of such a policy. CGE models are becoming a widely used tool for quantifying the costs and benefits of environmental policies. CGE models are not intended to forecast the values of economic variables, but rather to provide useful insights that may help policymakers to undertake more informed policy actions. Since they cannot be used for forecasts, CGE modelers are not compelled to compare their results with outcomes of policy changes in the world. They use the current theory and produce results from changes in the structure of the economy or of a policy experiment which can not be falsified. This problem results also from the fact that not many CGE models have a very solid empirical basis. Since CGE experiments analyze the results of actual reforms rather than hypothetical ones, it is important to improve the empirical assessment of these models. Since most CGE models are calibrated and not econometrically estimated, simulation experiments are required to check the robustness of the results given the limited quality of the deterministic calibration. Since CGE models are based on assumptions concerning the economic development (elasticities of substitution and transformation, technical change, exogenous variables), it would be misleading to base policy decisions on a specific numerical result. Stochastic simulation studies can be thought of as a statistical form of sensitivity analysis which can generate a distribution of possible outcomes through “Monte Carlo” methods.

An extension often mentioned in survey articles is research on specifying alternative market structures in CGE models. With a few exceptions (Harris (1984)), most models assume that all markets are competitive. However, there is not one but many models on imperfect competition and after all it becomes less obvious what has driven the model and its results. The same argument holds for modeling disequilibria in some markets of the economy. We know that disequilibria exist in the labor market and in the market for physical capital, and that changes in unemployment or in the utilization of capacities are often the short-run consequences of sudden changes in the magnitude of an environmental policy instrument. In such cases some model builders modify their approaches by allowing explicitly for partial disequilibria in the labor and capital markets by adopting theories on under- or overutilization of the primary factors of production. In principle, economic theory offers a variety of possibilities for future research: imperfect competition, endogenous technical change, adjustment costs in the labor market and in capacity formation, the role of infrastructure, uncertainty in supply of non-renewable resources, etc. However, the more complicated the model, the more it becomes a black box. Since no model can completely represent reality, a choice has to be made about what key features are to be included in any modeling approach.

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