Spatial-economic-ecological model for the assessment of sustainability policies of the Russian Federation

Project 213091

D1.1
Overview of the relevant literature

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1 Introduction

This literature review has been prepared for the SUST-RUS project (Spatial-economic-ecological model for the assessment of sustainability policies of Russian Federation). The goal of researchers behind this project is to develop and implement for Russia an integrated spatial-economic-ecological modeling approach, which represents the state of the art and can be used to assist policy makers in their choice of sustainability policies.

The SUST-RUS project has clear orientation for practical policy applications. Analysis of policy measures of appreciable magnitude and applicability, as evident in those concerning sustainable development, call for careful modeling of major policy trade-offs in the decisions involved. Accordingly, it seems natural that economic thinking should be the central point in this modeling exercise. Indeed, economics is considered the science of resource allocation, both in normative and positive senses, and as such, is heavily involved in analyzing trade-offs, agent incentives and all the minutiae of actual-decision making by productive agents. As many a baffled politician can attest, the way people react to suggested policies is the single most important factor in transforming the nature of intended consequences of those policies, sometimes out of all recognition.

This review will cover the class of models commonly referred to as computable general equilibria (CGE), specifically set up to answer policy questions of sustainable development, especially in its environmental and energy aspects. The main reason for limiting the overview with this class of models is the decision of the SUST-RUS modeling crew to set up this kind of model for Russia. In defence of this decision we can mention that CGE modeling tradition consistently provides the single most effective and widely used policy assessment tool in economic matters in the world. Moreover, the comprehensive nature of the CGE class of models (their "general" flavor and highly detailed level of disaggregation in representing major economies) lends them naturally to studying environmental effects of economic activity.

1.1 Concept of sustainable development

Before turning to reviewing the existing literature on modeling sustainable development issues, it is useful to clarify the meaning of "sustainable development" itself. Surprisingly, this is not easy to do. The usual approach to "sustainable development" defines it as development "which meets the needs of the present without compromising the ability of future generations to meet their own needs" (see WCED, 1987). Although attractive, the exact nature of this definition is difficult to pin down. The terms used in it do not happen to have exact formulations themselves, as is often the case in ethical matters. It is not clear what is meant by "needs" of either current or future generations and how their relative merits are to be compared. If, for example, current generations need oil and other fossil fuels on the brink of depletion, does it mean that future generations will need them too? If so, in what amount? Will the renewable sources of energy, as new, better technologies come on-line, satisfy the wildest dreams of future generations?

We see that many of these questions depend crucially on the way the "needs" of different people are ascertained, added up, and compared. Thus, the question of sustainable development is close in nature to distributional aspects of wealth accumulation and questions of equity. Accordingly, this question is overly complex, and we can only hope to fill in some of the blanks in our understanding. The first step in this direction would be an effort to collect and prioritize the set of indicators in different aspects of human life that could plausibly be considered part of sustainable development. Much of the work along these lines has been carried out by the United Nations Commission on Sustainable Development, established in 1992. Closer to actual policy making, in June 2006, the Council of the European Union has adopted a "Renewed EU Sustainable Development Strategy" (see CEU, 2006). This document distinguishes seven key challenges in the European sustainable development:

1) climate change and clean energy,
2) sustainable transport,
3) sustainable production and consumption,
4) conservation and management of natural resources,
5) public health,
6) social inclusion, demography and migration,
7) global poverty and sustainable development challenges.

We are concerned here with the way current modeling approaches are able to help in meeting these challenges, and the important spadework of reviewing and systemizing sustainable development indicators, as they are covered by today's modeling techniques, has been done in Böhringer and Löschel (2006). Among areas of interest for sustainable development, quoted in that paper and covered to various degree by the current modeling techniques, we can distinguish the following:

- economic growth,
- poverty and social exclusion,
- public health,
- climate change and pollution,
- management of natural resources.

Economic growth in its various aspects is heavily explored by theoretical economics. Applied literature to date has also much to say on the subject.

Poverty and social exclusion are captured to some degree by distributional and equity aspects of economic models. Public health and climate change questions are addressed in environmental modules (in particular, see Mayeres and Van Regemorter, 2003). Finally, the management of natural resources is successfully modeled in parts of models concerned with energy.

In the body of this report we will try to acknowledge the ways actual models under review cover these topics.

1.2 Computable general equilibrium in policy analysis

There are several classes of models used in policy analysis and the computable general equilibrium is only one of them. We can also mention large macroeconometric models (such as NEMESIS), dynamic macroeconomic models in neoclassical tradition (see Ljungqvist and Sargent, 2004), partial equilibrium models (as PRIMES model, see Capros, 1995) and various stylized models in theoretical economic literature. Still, CGE models present well-known advantages that make them indispensable in policy assessment in a wide range of applications.

The major feature of CGE models is their unsurpassed level of disaggregation of economic activity. Typical CGE models incorporate between 5 and 50 sectors of economics. This proves to be especially useful while analyzing the consequences of policy decisions influencing different types of economic activity in different ways and forcing rippling effects across the economy. Needless to say, many policy measures addressing questions of sustainable development fall into this category.

Another general feature of CGE models is their solid microeconomic theoretical foundation. This makes for high plausibility of results and predictions that depend on mere time trends to much lesser degree than those of large macroeconometric models. The fully optimizing behavior of agents in static CGE models makes them a good approximation of reality and justifies their ubiquity as the workhorse of policy analysis.

Finally, CGE models are “general” in nature. This means that they consider the economic regions in question in their entirety, comprehensively modeling economic activity, so that the indirect effects of changes in one sector of economy on all of the other sectors are safely captured. Again, this feature is indispensable in studying effects of policy changes indirectly affecting many economic sectors.

We would like to mention that CGE models are concerned with the real economy and are poorly equipped to deal with financial matters and questions of uncertainty. Those two are the domains of dynamic macroeconomic models in neoclassical tradition. As a consequence, CGE models do not usually deal with questions of monetary policy, financial intermediation and the such.

Another weakness of CGE models can be found in the treatment of dynamics and associated matters (like capital accumulation and technical change). Given the recent constraints on computing power, many of the better-known CGE models took the path of "recursive-dynamic modeling", where agents plan investment and saving myopically, not taking into account all available information about expected future variables. This feature has stemmed from the trade-off with the highly detailed level of disaggregation in the economy. To CGE modeler's credit, this weakness is being successfully dealt with in the most recent models, as they adopt fully forward-looking dynamic framework (see Dellink et al., 2004; Paltsev et al., 2005).

Finally, the last major and persistent weakness of CGE modeling tradition is its rather lax empirical inference standards. Typically, structural parameters in CGE models are not estimated (in the econometric sense of the word), but "calibrated" or "benchmarked". The procedure boils down to fitting the variable values in the model to the initial (benchmark) data, consisting of input-output flows along with National Accounting statistics for a chosen year combined into the so-called Social Accounting Matrix (SAM). The only criterion for validity consists in the ability of the model to replicate the initial state of the economy. In other words, under this approach we estimate parameters using only one data point, so we cannot reliably tell whether there is any decent fit at all. The validity of the constructed model and the reliability of its results remain, thus, unconfirmed.

Given the way structural relationships are usually parameterized in CGE models (with heavy use of constant elasticity of substitution functions), not all of the parameters can be pinned down using the procedure above. The most important of them are called elasticities of substitution (between goods), and they are responsible for how easily one of the goods can be substituted for another in production or consumption. A typical CGE model uses extraneous sources of information for assigning values to missing elasticities. In the best-case scenario, researchers use results of econometric studies that estimated elasticities of substitution in question. In the worst case models use "expert" estimates, based on opinions of selected experts in the field (see, e.g., Cossa (2004) describing the procedure for finding elasticities in EPPA model).

According to Hertel et al. (2007), even the less objectionable approach of using econometric estimates in the literature faces at least three major problems. The use of point estimates disregards information on distribution of estimated parameters. Biases in estimates emerge due to problems of typical estimation techniques in the source studies. And finally, additional biases might be introduced by the mismatch between the data in the source studies and the variation of the data, corresponding to the policy experiment in the CGE model in question. Some of the more ambitious CGE projects strive to address the criticism, associated with fitting values to elasticities of substitution, by collecting the relevant data and conducting econometric estimations inside the project itself (Hertel et al., 2007).

Despite the above-mentioned shaky empirical foundations of the CGE modeling approach, we should remember that most of those shortcuts are made because of the demands on models placed by their *raison d'être*: assessment and assistance in actual policymaking. Thus, the dearth of solid econometric studies estimating relevant elasticities of substitution and methodological difficulties of their conducting often make the approach to parameterizing taken by CGE models the best possible alternative.

Structurally, computable general equilibrium (alternatively called applied general equilibrium, AGE) models adhere to the Walrasian general equilibrium concept, as understood in the tradition of Arrow-Debreu (Debreu, 1972).[1] A model in this tradition specifies separately consumers and producers. Consumers are characterized by preferences so that they try to maximize their utility, derived from consumption, subject to budget constraints. Producers (firms) maximize profits, given their technology. With the view of policy assessment, the model introduces government sector that is collecting various taxes, disburses subsidies, imposes tariffs and quotas, consumes some of the goods, takes part in production and, finally, redistributes part of its tax receipt back among consumers. Given solutions to problems of consumers and producers the demand and supply of all goods in the economy are formed. Finally, prices on the markets adjust in such a way that "markets clear"; in other words, the supply of every good is equal to the demand for it.

Special provisions are made to deal with difficulties posed by the limits to generality of any policy-oriented CGE model. The corresponding procedures are typically called "closures" and on the technical level boil down to prescribing which of the variables to consider exogenous (determined outside of the model) and which – endogenous (determined inside the model out of behavioral and functional relationships). In a narrower sense, closure procedures often deal with problems posed by the recursive-dynamic approaches to modeling dynamics. In this setting, temporal changes in economic variables are driven by the way investment is modeled and there is no generally accepted single way of doing it. Notice that in the fully-rational forward-looking equilibrium this problem does not exist as investment is determined by savings – which can also be interpreted as a specific "neoclassical closure rule". Yet, remembering that savings are equal to the sum of private investment, government budget surplus and current account balance, it is not usually enough to "close" the behavior of private investment alone. Thus, additional closure rules concern, for example, the balance of trade – if the rest of the world is not modeled at the same level of detail as the small domestic economy, it is necessary to make assumptions on how the balance of trade is maintained.

Much of the controversy surrounding closure rules stems from poorly resolved in the theoretical literature issues of the right way to approach

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[1] For an alternative view on the basics of CGE and AGE as well as a potted history of the subject, see Mitra-Kahn (2008).

macroeconomic modeling. Thus, models might utilize the neoclassical closure (investment fully endogenous and is determined by savings), neo-Keynesian closure (introducing rigidity in wages), the "General Theory" closure (relaxing full-employment constraint) and so on. For a helpful discussion of this issue, see Rattsø (1982).

1.3 Organization of the review

In the next chapter we will consider in detail the economies of specific CGE models designed for assisting sustainable development policies. For a more comprehensive review of CGE models the reader can turn to various surveys: Bhattacharyya (1996); Partridge and Rickman (2007); Shoven and Whalley (1984, 1992).

The class of CGE models concerned with environment usually has better representation of the energy sector (with a higher level of disaggregation and particular care taken in specifying production structures) and sets up a separate environmental module. Besides accounting for emissions and allowing for pollution abatement, the environmental module is supposed to help in evaluating (in monetary terms) of benefits and costs of environmental policies so that it were possible to incorporate them in welfare analysis. Occasionally, care is taken to account for various feedback effects from environmental activity back into the economy: improvements in health, loss of labor productivity due to pollution, medical expenses associated with combating health effects of environmental degradation (see Mayeres and Van Regemorter, 2003). Chapter 3 is devoted to the techniques behind modeling of environmental modules in the CGE models under review. For comprehensive surveys of CGE modeling of environmental issues, turn to Bergman (2005) and Conrad (2001).

Finally, in chapter 4 we draw some conclusions.

2 Economy

The heart of any economy-energy-environment CGE model is in the model of economy. In this chapter we will discuss economic modeling features of specific environmental CGE models in view of their declared purpose. Table 2.1 presents models under review with their purpose and references.

A major feature of the CGE approach to economic modeling is the ability to separately consider different sectors: specific industries, households and government. The only information needed for linking the sectors in the model is prices (along with tax rates). After solving the problems of each of the sector players, the final step in solving the model is meeting so-called market clearing conditions, where quantities of separate goods demanded by all sectors should be made equal to the quantities supplied by all sectors.

Before reaching this final step, however, each of the economic sectors is modeled largely independent of each other. In this chapter of the review, like in the models themselves, we will exploit this modularity advantage and consider setting-up of different sectors in sequence. We will start with the firm behavior in industry sectors in section 2.1. The important question of escaping the straightjacket of perfect competition, naturally arising in CGE modeling tradition, is explored in section 2.2. Household behavior is considered in section 2.3 and government sector in section 2.4.

2.1 Firm behavior

Typically, producers in a CGE model are assumed to behave in a competitive manner and maximize profits, taking all prices (including wages for labor, rental prices of capital and land, prices of intermediate inputs and the price of output) as given:

$$\max_{x_1,\ldots,x_m,k,l,t} \quad p f(x_1,\ldots,x_m,l,k,t) - \sum_{i=1}^{m} p_i x_i - wl - r_k k - r_t t \qquad (2.1)$$

(here $x_1,\ldots,x_m$ are intermediate inputs, l is labor, k – capital, and t – land). The production function, given by f, is assumed to be of neoclassical nature: increasing in its arguments and concave so that the firm's problem (2.1) is well-defined.

The bulk of CGE models goes further and assumes the production function f presenting constant returns to scale (CRS); this means that increasing all inputs in production by a single factor boosts the output by the same factor. This assumption allows us to simplify derivations,

Table 2.1: Models under review

Model	Purpose	Sources
GEM-E3	Representation of interactions between the economy, the energy system and environment in the world and EU countries	GEM-E3 (2006); see also Capros (1995); Mayeres and Van Regemorter (2003)
EPPA	Projections of economic growth and anthropogenic emissions of greenhouse related gases and aerosols	Paltsev et al. (2005)
MMRF-GREEN	Measuring of environmental impact through energy usage and greenhouse gas emissions by fuel, user and region in Australia	Adams et al. (2003)
GreenMod II	Energy and environmental policy assessment and support for decision-making in energy and environmental matters in Belgium	Bayar et al. (2006)
GTAP-E	An extension of the CGE model GTAP incorporating energy substitution for environmental policy assessment; specifically, greenhouse gas (GHG) mitigation	Burniaux and Truong (2002); see also McDougall and Golub (2007); Hertel (1999)
ISEEM	Representation of Belgian economy with particular emphasis on spacial features and transport	Heyndrickx et al. (2009)
TEQUILA	Ascertaining the environmental impacts of changes in trade regimes as well as assessment of the trade-offs between growth and the environment in six countries (Mexico, Costa Rica, Chile; China, Indonesia and Vietnam)	Beghin et al. (1996); see also Beghin et al. (2000)
DEAN	Dynamic modeling of pollution abatement	Dellink et al. (2004); see also Dellink and Van Ierland (2006); Dellink (2000)
Model for Ireland	Analysis of the impact of a carbon energy tax on the Irish economy	Wissema and Dellink (2007)

since in this case marginal costs equal average costs, and the price of output is rigidly linked with the unit cost of production (price index), being a function of input prices:

$$c(p_1, \ldots, p_m, w, r_k, r_t). \tag{2.2}$$

Going even further, the functional form production functions in CGE models usually take is that of nested constant-elasticity of substitution (CES) functions. Specifically, a production function is set up as composition of functions of the following form:

$$\mathsf{ces}_{\sigma; a_1, \ldots, a_n}(x_1, \ldots, x_n) = \left(\sum_{i=1}^{n} a_i^{\frac{1}{\sigma}} x_i^{\frac{\sigma-1}{\sigma}} \right)^{\frac{\sigma}{\sigma-1}}, \tag{2.3}$$

where $\sigma > 0, \neq 1$ is the elasticity of substitution (between inputs $x_1, \ldots, x_n$) and $a_1, \ldots, a_n$ are called "share parameters" of corresponding inputs. A more detailed characterization of CES functions can be found in any intermediate microeconomics textbook, e.g. Varian (1992). We will only mention that the definition of a CES function by formula (2.3) can be extended by continuity to the following cases:

- $\sigma = 0$ (Leontief production function):

$$\mathsf{ces}_{0; a_1, \ldots, a_n}(x_1, \ldots, x_n) = \min \left\{ \frac{x_1}{a_1}, \ldots, \frac{x_n}{a_n} \right\}; \tag{2.4}$$

- $\sigma = 1$ (Cobb-Douglas production function):

$$\mathsf{ces}_{1; a_1, \ldots, a_n}(x_1, \ldots, x_n) = \prod_{i=1}^{n} \left(\frac{x_i}{a_i} \right)^{a_i/A}, \qquad \text{where } A = \sum_{i=1}^{n} a_i;^{1} \tag{2.5}$$

- $\sigma = \infty$ (linear production function):

$$\mathsf{ces}_{\infty; b_1, \ldots, b_n}(x_1, \ldots, x_n) = \sum_{i=1}^{n} b_i x_i, \tag{2.6}$$

  (where parameters b_i are obtained from formula (2.3) in the limit $\sigma \to \infty$ by holding constant not share parameters a_i, but rather $a_i^{1/\sigma} = b_i$).

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[1] Notice that this formula parameterizes all possible non-degenerate Cobb-Douglas specifications in a one-to-one correspondence. Indeed, suppose the general Cobb-Douglas function is given by $B \prod_{i=1}^{n} x_i^{\alpha_i}$, where $B, \alpha_1, \ldots, \alpha_n > 0$ and $\sum_{i=1}^{n} \alpha_i = 1$. Then, obviously, the reparameterizations are given by $\alpha_i = a_i/A$, $B = \prod_{i=1}^{n} a_i^{-a_i/A}$ and, in the opposite direction, by $a_i = \alpha_i B^{-1} \prod_{i=1}^{n} \alpha_i^{-\alpha_i}$, $A = B^{-1} \prod_{i=1}^{n} \alpha_i^{-\alpha_i}$.

Among nice features of the CES functions, making them the darlings of the CGE world, we might mention their parsimonious and intuitive parametrization: the elasticity of substitution σ has an immediate economic meaning and characterizes the degree of substitutability of inputs in production. Thus, from the point of view of CGE modelers, the choice in further specification of technologies is reduced to characterizing three distinct features of the model:

- the nested structure of production functions,
- the elasticities of substitution,
- the share parameters.

Notice that estimation of share parameters in the CGE tradition is performed by what is called benchmarking: the parameters are fitted to the benchmark snapshot of the economy, captured by SAM, and are directly linked to the shares of the corresponding inputs in production. Thus, the differences of interest between specifications of technologies in separate models might be found in the nested structure and the choice of elasticities of substitution.

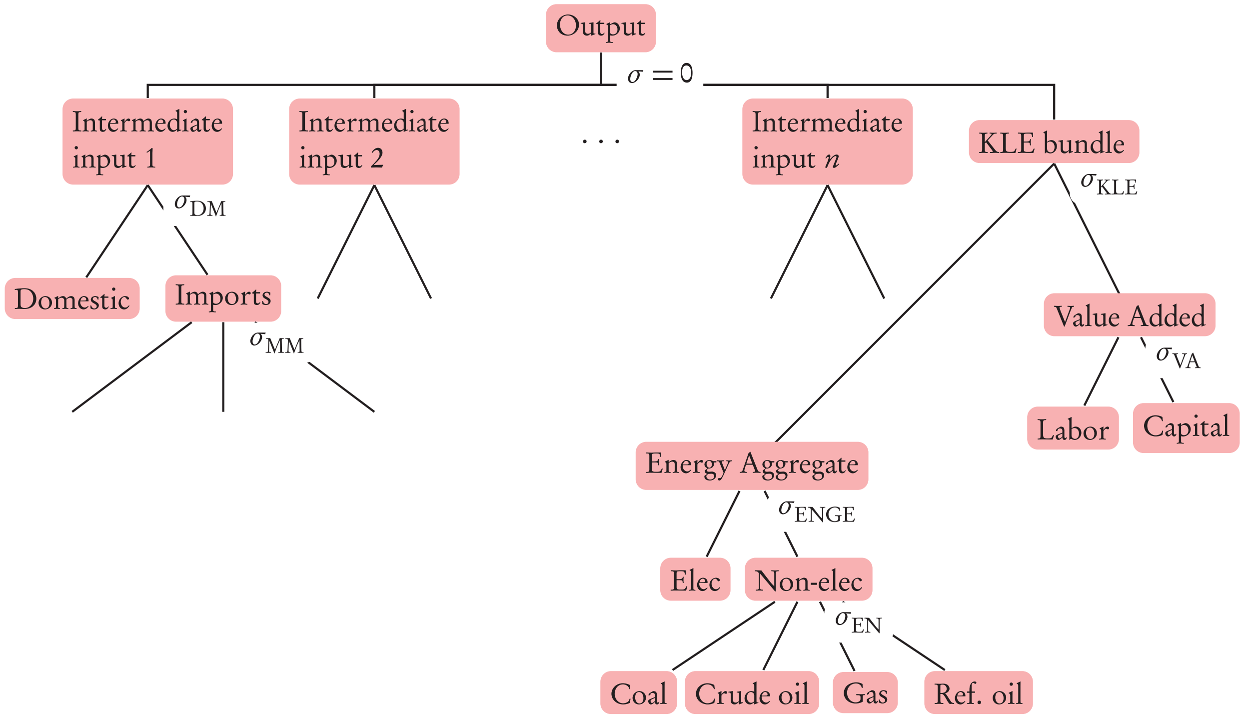
All models we are reviewing are interested in modeling environmental effects of economic activities. As such, all of them use particular care and additional disaggregation in the energy sectors. The nested structures of all models take non-generic approach to both modeling production in the energy sectors and the way energy inputs are absorbed in production of other goods. Only in the MMRF-GREEN model there is no specific treatment of the energy sectors (neither in terms of production inputs to other industries nor in distinct production functions in an energy sector). It might be an artifact of the origin of the model: unlike all the others, MMRF-GREEN was built on top of already existing generic CGE models for Australia (static MMRF and dynamic MONASH). Thus, development of the model in the "green" direction has been reduced to accounting of emissions and introduction of slapped-on simple abatement technologies.

The typical nested structure is presented in figure 2.1 (and is based on EPPA's treatment of production technology in the bulk of its industries).

Analyzing nested structures of production technologies in all models under review, we can discern several common practices:

- Armington assumption is used in combining domestic and imported intermediate non-energy inputs consistently across all models;
- often, intermediate non-energy inputs are combined with fixed shares (Leontief function) (EPPA, Ireland, GreenMod II, ISEEM);
- the top-level nesting is often Leontief for generic industries (EPPA, GreenMod II, MMRF-GREEN);
- capital, labor, land (if present) and energy are often combined into one bundle and meet intermediate non-energy inputs at the top level (EPPA, GreenMod II, MMRF-GREEN, GTAP-E, TEQUILA (with intermediate input goods *bundle* as input at the top level) and Ireland).

Figure 2.1: A typical nested CES as production function in the CGE models under review (the structure of production in most industries in EPPA)



A striking exception to the last point presents GEM-E3, where at the top level capital is combined with labor – energy – non-energy intermediate inputs bundle (LENI). In fact, this model combines non-energy intermediate inputs with labor and fuels at level 3 into LNIF bundle, which then is combined into LENI bundle along with electricity at level 2. Clearly, GEM-E3 provides a non-conventional way of looking at things and might suggest that there are better substitution possibilities among labor, energy and intermediate inputs than between labor and capital. According to the manual, this peculiar nested structure was chosen in accordance with an econometric study by CES and the Belgian Planning Office on substitution possibilities in 10 Belgian industrial sectors. That study found the long-run elasticities of substitution between all inputs rather low, especially in the case of capital as substitute for the rest of the inputs. The highest substitution possibilities were found between labor, non-energy intermediate inputs and fuels.

The predilection to use Leontief functions for combining non-energy intermediate inputs can be explained by the residual character of those inputs in production (i.e., they are not specifically addressed in the modeling process as energy inputs are). Thus, in a generic production technology there are no technical reasons to believe in major substitution possibilities between them, and the expected low level of substitutability might safely be modeled with the extreme Leontief case.

The tendency to have low substitutability at the top nest could also be explained by the nature of the modeling process. All *a priori* significant substitution possibilities between *actual* inputs (as opposed to bundles) call for careful handling, since they will be the most important source of indirect policy effects in the model. Presumably, this handling is best done at a level with carefully controlled substitution possibilities. The lowest possible level of nesting with clearly specified (constant) elasticities of substitution is the natural place for such highly substitutable inputs. Conversely, at the top level we should expect lower substitutability.

However, this is not a universal rule. There are a few cases where other considerations, drawn from the knowledge of technological processes, override this rule of thumb. Thus, in the nesting structure for the electricity generation sector in EPPA, “Wind and Solar Power” electricity generation is combined with “Domestic Output” (generation by conventional technologies) allowing for some finite substitution (due to the irregular nature and inconvenient location of wind and solar power generation). At the same time, “Domestic Output”, naturally, is modeled at a lower level as a combination of perfect substitutes – electricity generated by “Conventional Fossil”, “Nuclear” and “Hydro” sectors. Nevertheless, the production functions for electricity generation in the latter sectors adhere to the conventional nesting structure of generic industries (see figure 2.1).

Two of the reviewed models are similar in the meticulous way both of them set up production structures of assorted industries: EPPA and GreenMod II. Both models distinguish between generic industries, energy industries (supply and distribution of conventional energy) and agriculture. EPPA goes even further and models separately the electricity generating industry (as it tries to model explicitly non-conventional sources of electricity, such as wind and solar power, and recognizes imperfect substitutability of their output with that of the conventional sort). Furthermore, production structures of these groups of industries turn out to be surprisingly close to each other in the two models.

Thus, the generic industry production structure in GreenMod II is almost the same as that presented in figure 2.1 for EPPA. The only difference is that GreenMod II modelers chose to bundle capital with energy before nesting it with labor in capital-labor-energy bundle at the second level (EPPA bundles capital and labor first and energy second).

In both models there is the same treatment of the energy bundle (combination of electrical energy and the fuel energy bundle). The GreenMod II model is more detailed in disaggregation of the fuel energy bundle: it has coal, petroleum coke, gasoline, heavy oil, gas oil, coke oven gas, refinery gas, natural gas and other combustibles as the types of fuels accounted for against EPPA's coal, oil, gas and refined oil. This might be explained by the more detailed level of data at the disposal of GreenMod II creators (who took great pains at collecting the highly disaggregated data on 62 production sectors in three Belgian regions at the initial stage of their project). On the other hand, EPPA's modelers might have been hampered by the scale of their project (the whole world) that might have prevented further disaggregation in the data collection process.

The meticulous approach in the two projects can be attributed to the thorough and well-funded nature of the projects themselves. In case of EPPA it can also be explained in connection with one of the goals that the project strives to achieve: construction of the structure of physical flows paralleling that of value flows of SAM. This might be extremely helpful in the exact accounting of emissions, so important in environmental modeling. At the same time, it might lead to specific patterns of data disaggregation and the necessity of refining production structures that we can witness in the current version of EPPA.

Among interesting specific features of the MMRF-GREEN project we have already mentioned its defective approach to incorporating the energy sector in the production structure, coming from the legacy constraints imposed by the model's precursors. Other important features include the additional layer of bundling domestically produced goods, introducing imperfect substitution between goods produced in different Australian regions (eight in total). This reflects regional aspects of MMRF-GREEN modeling, which strives to account for interregional differences in all sectors (including government). Also, MMRF-GREEN, as well as TEQUILA, is able to disaggregate labor further according to "skill". Given the availability of data disaggregated along these lines in both projects, this presents an opportunity to explore distributional and equity effects of analyzed policy measures.

The ISEEM model distinguishes buildings and land use in its production functions, so it models those inputs separately, bundling them together at the last but one level and then combining this bundle with the capital – energy – labor – intermediate inputs bundle (KELM) at the top level. The KELM bundle is a combination of the capital – energy and labor – intermediate inputs bundles, each of which has a rather standard decomposition itself.

The model for Ireland distinguishes between generic industries and electricity generation. The structure of the latter is given by consecutive bundling: starting with oils and natural gas combined into the liquid fuels bundle, then combined with coal into the fossils bundle, then along with electricity into the energy bundle, with capital into capital-energy, with labor into labor-capital-energy, with non-energy intermediate inputs into conventional-source electricity, with renewable sources into the last-but-one bundle, and finally, combined with peat (in fixed shares!) into the final production of electricity. The production structure for generic industries is similar (except for the absence of renewable sources of electricity and more generic treatment of peat, which is introduced into the fossils bundle together with coal through "solid fuels" bundling).

The production function structuring in the model for Ireland seems more *ad hoc*, compared to the other models, and is, probably, based on the availability of information on elasticities of substitution. It is mentioned in Wissema and Dellink (2007) that the elasticities of substitution between labor and the capital-energy bundle, as well as between aggregate energy and capital are taken from Kemfert (1998) where they are estimated for Germany. It is also mentioned that the choice of sequential bundling of capital and energy and then with labor is again "based on Kemfert (1998), who concludes that this fits the German industry best overall[;] GTAP-EG (Rutherford and Paltsev, 2000) inspired the remainder."

2.2 Industry structure

Given the theoretical roots of the CGE approach in the Walrasian and Arrow-Debreu tradition, it is not surprising that almost all of the models assume perfectly competitive environment in all markets. Unlike theoretical models though, CGE models are geared towards policy assessment and so should better reflect reality in specific situations – perhaps, at the expense of simplicity and transparency. In many applications it seems highly unlikely that the assumption of perfect competition can be justified, making the results of CGE model simulations unreliable. Thus, incorporation of some forms of imperfect competition and associated industry structures (monopoly, oligopoly and monopolistic competition) present a challenge to CGE approach.

This challenge is formidable, since economic theory (as major source of legitimacy for CGE modeling approach) is still very far from the adequate way of incorporating non-competitive issues into the general equilibrium framework. According to the current state of theoretical knowledge, strategic interactions (as in oligopoly and monopoly) should be modeled in the game-theoretical framework. This framework depends crucially on specification of strategy spaces (the sort of actions available to agents to decide upon), and the ensuing Nash equilibria turn out to be sensitive to the exact nature of the chosen strategy spaces. This sensitivity can be attributed to the inherent "multiplier" effects in strategic decision-making. While deciding on his actions, each of the agents has to take into account the choice of actions by other agents, who in turn feed the presumed behavior of their counterparties into their own calculations, and so on and so forth. Notice that in general-equilibrium setting with perfect competition this chain of dependencies is short-circuited: the large number of competitors allows agents to disregard the behavior of any single competitor and only take into consideration some aggregate variables (like prices). Simplifying matters even further, these aggregate variables can safely be taken as given since actions of a single agent cannot influence appreciably their values.

Accordingly, economic theory is able to suggest only (somewhat deficient) incorporation of monopolistic competition into the general equilibrium framework. Indeed, producers in a monopolistically competitive industry are assumed to be as small as in a perfectly competitive case and so behave non-strategically (not taking into account the behavior of their individual competitors). Yet certain complications persist, as individual demand functions should be calculated in this case *before* solving the producer's problem so that simple market clearing conditions are not enough to close the model.

Among models under review only GEM-E3, GreenMod II and ISEEM claim to incorporate some form of imperfect competition. Despite this declaration, the discussion of the issue in the reference manual of GreenMod II available to this reviewer (Bayar et al., 2006) is rather sketchy, so it is rather hard to evaluate the claim of GreenMod II creators. GEM-E3 modeling team provides reasonable description of their approach whose synopsis we are going to present next. More comprehensive review of incorporating imperfect competition into CGE models can be found in Willenbockel (2004).

The approach taken by GEM-E3 and ISEEM is based on the concept of the "love of variety", introduced in Dixit and Stiglitz (1977). Consumers are assumed to prefer more kinds of goods imperfectly substitutable in consumption bundle rather than less. Even though this concept is already present in a crude way in ordinary convex preferences (consumers prefer to consume all of the goods in reasonable amounts rather than discard some of them altogether), the specific functional form of CES functions presents especially nice way of modeling this concept. Thus, the Dixit-Stiglitz preferences (or an aggregate good of an industry) are represented by

$$Q = \mathsf{ces}_{\sigma;1,\ldots,1}(q_1, \ldots, q_n). \tag{2.7}$$

Notice that shares are presumed to be all equal to 1, so that all of the goods are perfectly symmetric and their only distinction is found in their imperfect substitutability. To obviate the need for disaggregation of sector input-output flows all the way down to a single firm's level, GEM-E3 and ISEEM modelers maintain this symmetry assumption on the production side as well so that the only new parameter for the industry to keep track of in data is the number of comparable major producers: n. It is easy to see that the derived demand for each of the goods will be given then by

$$q_i = n^{-\frac{\sigma}{\sigma-1}} Q. \tag{2.8}$$

The "love of variety" is easy to see here: to maintain the same level of "consumption" Q with higher levels of variety n is easier: the total level of production $\sum_{i=1}^{n} q_i = nq_i = n^{-1/(\sigma-1)}Q$ is lower.[2]

Notice that to have a well-defined number of firms in this setting (instead of infinity in the perfectly competitive environment long-term), there should necessarily be economies of scale in production. Those are introduced by allowing fixed costs, expressed in primary factors (labor, capital).

Rather than modeling monopolistic competition in line with Dixit and Stiglitz (1977), GEM-E3 modelers assume oligopoly. We already know that the difficulties of this approach concentrate in setting up the strategic environment. It is assumed that firms compete by Cournot so that they choose the level of output, taking the levels of output by competition in equilibrium fixed and allowing prices to adjust. Nevertheless, the question of determining the demand function that each firm faces in its output market presents a formidable obstacle. The firm's decision maker is considered to be boundedly rational, where complexities of calculating the true demand for his product force him to assume that the demand for the aggregate Q takes a simple *ad hoc* form of a constant elasticity (Ω) function. Then it is possible to derive the firm's own demand elasticity (ω), depending on Ω and the number of firms in the industry n.

Finally, the optimizing oligopolist chooses the amount of output and the corresponding price p according to the usual markup equation (given the elasticity of demand):

$$p = \frac{\omega}{\omega - 1} c, \tag{2.9}$$

where c is the marginal cost of the firm.

Given those simplifying assumptions (firms' perfect symmetry and bounded rationality of their decision makers), the number of parameters

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[2] It is assumed $\sigma > 1$; in fact, σ should be large so that substitutability is significant, though not perfect ($\sigma < \infty$).

needed for calibration in this setting is reasonably small: the number of firms n, the levels of fixed primary factors and the elasticity of demand for the aggregate good Q. The number of firms is parameterized by calculating Herfindal indices of industries, the levels of fixed primary factors are taken from engineering studies estimating minimum efficiency scales for industries, and finally, the demand elasticity is teased out of the zero profit assumption in the benchmark year: the price markup can be found given that the operating profit should cover the fixed costs.

Imperfect competition in the ISEEM model is modeled along the same lines as in the GEM-E3 setting, though the matter is simplified considerably by assuming monopolistic competition with free entry (as opposed to oligopoly). In this case the elasticity of demand for the output of each firm is easy to find and happens to be equal to the elasticity of substitution of the Dixit-Stiglitz preferences, introduced above.

The description of imperfect competition in the GreenMod II model (Bayar et al., 2006) is unsatisfactorily sketchy. It is claimed that in oligopolistic industries prices are determined with markups depending on the number of firms, whereas in monopolistically competitive industries firms use constant markups irrespective of the number of firms. In its own turn, the number of firms is determined out of the zero-profit condition. Again, as in the GEM-E3 model, fixed costs are introduced as fixed amounts of primary factors needed before starting any production. It is not clear whether markups depend on any elasticities of demand.

As a final note, we should mention that any treatment of imperfect competition in the CGE setting should be especially careful in the introduction of monopolists facing monopsonists. Indeterminacy of the derived demand (and supply) in this case calls for bargaining solutions and could unduly complicate any general-equilibrium model even further.

2.3 Consumer behavior

Consumer behavior in all models in neoclassical tradition is modeled using consumer preferences and rational behavior assumption. If preferences are expressed in terms of a utility function $U(c_1, \ldots, c_n)$, then the consumer chooses consumption levels of respective goods $c_1, \ldots, c_n$, maximizing his utility function subject to the budget constraint:

$$\begin{aligned} &\max_{c_1,\ldots,c_n} U(c_1, \ldots, c_n) \\ &\quad \text{s.t.} \\ &\quad p_1 c_1 + \cdots + p_n c_n \leq I, \end{aligned} \tag{2.10}$$

where I is consumer's total income which in the general equilibrium setting is further specified as coming from the value of the consumer's endowments, redistributed firms' profits (to the consumer as their shareholder) and, possibly, government transfers.

Unlike production sector where dynamic consideration can often be reduced to questions of capital formation and many firms' problem often are static in nature, the same approach does not work on the consumption side. In a dynamic general equilibrium setting, intertemporal substitution of consumption is present in the utility functions' setup: preferences are defined not only over current consumable goods, but over those in all future periods as well (see formula (2.11) below). Yet, maximization of the total intertemporal utility is performed only in fully rational forward-looking dynamic models. In policy-oriented CGE models for a long time computing power constraints, taxed by the highly disaggregated intratemporal nature of the modeled world, prevented successful employment of rational forward-looking dynamics. Thus, many of those models exploit the "recursive-dynamics" approach, where consumers plan their future actions based on today's pricing information in the (erroneous in equilibrium!) belief that the same prices will prevail tomorrow. If intertemporal preferences are given by separable discounted instantaneous utility functions, as in (2.11) below, then this approach leads essentially to static consumer problems for each period solved in a chain (linked through savings), one after another.

$$\sum_{t=0}^{T} \beta^t u(c_{1t}, \dots, c_{nt}). \tag{2.11}$$

Even though many of the old considerations of computing power constraints are invalid today, the old modeling traditions and legacy standards persist. Thus, of all the models under consideration only DEAN (a relatively new model built from scratch) presents fully consistent forward-looking environment. Besides, creators of EPPA model have plans for rewriting their model as completely rational forward-looking one in future (see Paltsev et al., 2005).

Accordingly, we will restrict ourselves to discussing mainly static consumer problems in this chapter.

In many of the models under review (EPPA, DEAN, Ireland) utility functions are chosen in the specific functional form of nested constant elasticity functions, mirroring the situation in the production sector. We have already discussed reasons behind this choice in section 2.1; the same considerations are valid on the consumer side of the modeled economy.

Yet in some of the models (GEM-E3, MMRF-GREEN, GreenMod II, ISEEM and TEQUILA) a slightly different functional form is employed at the top nested level: linear expenditure system (otherwise, Stone-Geary utility function). This functional form was introduced by Stone (1954), extended by Lluch (1973), and is characterized by linear dependence of the corresponding demand functions on income. The utility function in this system is represented by a Cobb-Douglas function where consumed goods c_i enter only in amounts by which they exceed the fixed in advance "minimum consumption levels" $\underline{c}_i$:

$$U(c_1, \ldots, c_n) = \prod_{i=1}^{n} (c_i - \underline{c}_i)^{\alpha_i} \tag{2.12}$$

(here share parameters $\alpha_i > 0$ are such that $\sum_{i=1}^{n} \alpha_i = 1$).

This functional form is especially useful when trying to introduce non-representative agents into the picture so that it were possible to analyze distributional effects. Thus, all the models whose stated aims included analysis of distributional and equity effects employ them. Another important feature of this simple system is that it gets rid (though, probably, in an unsatisfactory way) of the unit-elasticity-of-income feature of all homogeneous demand systems (including CRS utility functions).

Furthermore, two of the models (GEM-E3 and GreenMod II) go even further and employ nested structures in utility functions with linear expenditure system at the two highest levels. Both of them first bundle consumable goods with LES function and then at the top nest add leisure into the bundle. Note that these are the only two models with explicit leisure in consumer preferences – which is also consistent with the more careful approach to distributional aspects of wealth creation, much of which comes from labor income. A particular care should be taken in applying the 2-stage budgeting procedure at solving the consumer's problem, as it assumes peculiar features as soon as we move away from CRS functions at the lower nesting level.

The 2-stage budgeting procedure is the workhorse in solving either consumer's or producer's problem when dealing with nested CRS production functions. The first step consists in solving separately the problem at the top level, given the aggregate price of the bundled (at the second level) commodities in the form of their price index (alternatively, unit expenditure function or unit cost function). The second step allows to find unbundled commodities' levels given the known level of their bundle by minimizing the cost of obtaining that level.

It should be noted that generally, the 2-stage budgeting procedure in this specific form no longer works when the functional form at the second nesting level is not CRS. Intuitively, it happens because the marginal cost associated with a non-CRS production function diverges from the average cost. Thus, whereas the shadow price of the bundle, equal to its *marginal* cost, should be used in the top level maximization problem to get the correct first-order conditions, the budget constraint could be met only with the *average* cost used in the role of the bundle's price.

Still, in uncomplicated deviations from the CRS case, as presented by the functional form of a linear expenditure system, it is not hard to adjust the 2-stage budgeting procedure to get the correct results. It could be shown that the adjustment consists in subtracting the expenditure on the fixed minimum levels of the *second layer* commodities from the income in the budget constraint in the *first step* (top-layer maximization problem).

Compare this with formulae (1) and (2) in GEM-E3 (2006) and (2) in Bayar et al. (2006).

Among peculiar features of consumption structures employed in the rest of the models under review, we can mention the unique way savings are treated in TEQUILA and EPPA. Despite being avowedly dynamic, savings in both models enter directly into the instantaneous utility functions at the top nesting level. This looks like an artifact of an earlier static incarnations of those two models. TEQUILA modelers mention that the savings entering their utility function are sensibly deflated by the consumer price index, thus giving savings in real terms.

It could be noted that most of the employed structures of consumption are rather uncomplicated – often with no nesting at all or only one nesting in the presence of leisure explicitly entering utility function (GEM-E3 and GreenMod II). True to form, with its careful modeling of technical issues that might give rise to emissions, EPPA proves an exception. The nesting structure of consumption in EPPA is very elaborate. Utility is derived from the combination of savings and the bundled total consumables at the top level. Total consumables are bundled from transportation services and "other consumables". Other consumables are combined from the energy bundle and non-energy bundle. The energy bundle is a combination of separate fuels and electricity at the lowest nesting level. The non-energy bundle consists of all ordinary consumption goods. The transportation bundle is very detailed itself and is combined from purchased transportation services and a "private autos" bundle. The latter combines refined oil with a bundle of services (branching out at the lowest level into maintenance, insurance, parking, etc.) and "other industries products" (representing purchased vehicles proper).

In view of the declared aims of EPPA project, it is easy to see the logic behind this fine structuring of consumption as the whole and that of transportation services in particular. All of the specific processes that might lead to emissions are present in fine detail. Needless to say, the goal of EPPA modelers to construct physical flows connected with emissions in parallel with SAM is also helped along by this approach to structuring consumption.

Another feature of note in EPPA model is its treatment of the elasticities of substitution between non-energy consumable goods. It is assumed that those elasticities change with time as a function of per capita income growth between periods. Thus, not only are consumer preferences rendered unstable, the nature of this instability is made depended on an endogenous economic variable – per capita income growth.

That being said, however, it is useful to keep in mind the extremely long-run nature of EPPA forecasting as declared in its objectives. The necessity to account for clear trends in consumable goods' shares in such time horizons calls for an adjustment to CRS utility functions, whose homogeneity tends to result in stable shares reflecting unitary income elasticities. Hopefully, the EPPA project is envisioning radical changes in the intertemporal utility function in its future forward-looking dynamic version of the model that will be able to account for these secular trends.

2.4 Government sector

The government sector is considered separately in CGE models due to the special role government plays in the economy and environmental regulation. Furthermore, the purpose of most CGE models is connected with policy analysis so that the way various policy measures originating in the government sector feed into economic and environmental conditions is of particular interest.

In any discussion of modeling government sector in the economy, it is necessary to look into the way government revenues are formed: taxes and import tariffs. The question of subsidies is also close to this part of the government structure. If there are several levels of government in the model (federal, regional and local), it is usually necessary to model properly transfers between them, as they constitute a significant source of income on the regional and local levels. Government consumption is a major outlay on the expense side of the budget. Government investment might be modeled in the simple residual manner (depending on the way the modeled government budget is closed); otherwise, the modeler has to come up with a theory for the government investment policy. Finally, transfers to agents are considered, with particular care taken if the model is concerned with redistributive efforts of the state.

All of the models consider explicitly taxation as a major source of government revenue. Direct taxes usually include taxes on primary factor income such as personal income taxes, taxes on capital and property. Social security contributions, from both the employer and employee sides, are treated similarly to the labor income tax. Rarely, if ever, are considered inheritance taxes since their nature can only be captured in the overlapping-generations (OLG) setting, inimical to recursive-dynamic nature of most of the CGE models. Indirect taxes include excise taxes, VAT, sales taxes, other taxes on consumption, various commodity taxes, franchise fees, stamp duties, statutory levies and other production taxes. In the context of environmental CGE models, special treatment is reserved for energy and emission taxes.

The universal way taxes are wired in the structure of the model is by placing a wedge between prices on the supply and demand sides. Thus, if the price of the output product at the factory gate is given by p, then the price that the consumer of this product (or a firm that uses it as an intermediate input) faces will be $(1+\tau)p$, where τ is the corresponding tax rate. In a similar manner, a production subsidy makes the output price the producer faces $(1+s)p$ (as opposed to the "factory-gate" price p), where s is the rate of the subsidy.

For most of the taxes, the rate is given explicitly, whereas for some of them (e.g., excise taxes), it should be calculated, since the tax is levied per physical unit of the underlying commodity (factor).

Thus, a typical price the consumer faces (see Bayar et al., 2006) is given by

$$(1 - s_{\text{cons}})(1 + t_{\text{excise}})\left(1 + t_{\text{vat}} + t_{\text{other}}\right) p, \tag{2.13}$$

where s_{cons} is the rate of the consumption subsidy, t_{excise} is the inferred rate of the excise tax, t_{vat} is the VAT rate, and t_{other} is the tax rate of "other consumption taxes". It is useful to distinguish between all these different forms of taxation in the model and not to combine them into one equivalent tax for several reasons. Easier interface with data in its raw form (obviating the need for calculating the combined equivalent tax) is one of them. More to the point, different tax rates might vary in different ways across regions and commodities. Finally, policy experiments simulated in the model might change some of the tax rates, but not the others. In view of the last point, the TEQUILA model goes even further and introduces separate common factors inside tax rates that might make it easier to model uniform reduction in, say, all production taxes.

With several levels of government present, like in ISEEM, some of the taxes might be collected at the same rate across regions and the tax receipt be distributed in fixed shares across government branches in question. This is captured by the direct introduction of fixed factors when calculating tax revenue of the responsible government branches (see Heyndrickx et al., 2009).

The only non-trivial issue in modeling taxation concerns non-linear tax schedules, prevalent in personal income taxation and payroll taxes. The most satisfactory way of dealing with this issue would be by modeling income distribution in sufficient detail so as to capture and keep track of at least all income brackets. Only the models distinguishing consumers according to their income (GEM-E3, GreenMod II, ISEEM, TEQUILA) are capable of doing that. For the rest of the field is is necessary to distinguish between marginal and average rates of taxation and implicitly assume unchanging (in the face of policy measures) income distributions.

In the case of non-linear payroll taxation, the MMRF-GREEN model accounts for the size threshold in taxes payed by firms in Australia. As the model is interested only in small (log-linearized) changes in variables, it is able to do so without tracing the distribution of firms, needed in a more general setting.

The second source of government revenue is import tariffs and export taxes. Again, they are modeled as a wedge between import (export) prices on the demand and supply sides. The necessity to distinguish between different categories of imported (exported) commodities, incurring different tariff rates, is helped by the disaggregated nature of most of the CGE models.

Ad valorem tariffs are the easiest to model in this way, since they are stated in percentage terms of the value of imported commodities. Other tariff types present slight complications in calculating the corresponding tariff rates: specific duties, imposed per physical unit of an imported commodity, variable levies, designed to bring the price of an imported commodity in line with the price of a domestic equivalent, composite rates (combinations of *ad valorem* and specific rates), alternative rates (the higher of an *ad valorem* rate and a specific rate) and seasonal rates. For a discussion of modeling different kinds of tariffs and the important question of averaging tariff rates in an industry sector, see Laird (1997).

If the modeled country has many branches of government, it is necessary to model transfers between them. This specific issue is carefully addressed in models of Belgian economy (GreenMod II and ISEEM), since its network of government branches and transfers between them is the most convoluted. Suffice it to say, that one branch of government ("language communities") gets all of its revenue from transfers. The ISEEM model first introduces a fixed share of the total government income (including tax revenue and transfers) that is transferred; then the amount transferred is divided in fixed shares among different branches of government.

Government consumption is mostly distributed among public services and education services. In the bulk of the models under discussion, government consumption is modeled in a simplified manner so that it is not endogenized explicitly. Thus, it is either left to close the government budget (determined as a residual after calculating everything else on the expenditure and revenue side along with the budget surplus), or is fixed. The TEQUILA model fixes government consumption level at a benchmark level, MMRF-GREEN and DEAN treat it as a fixed share of the private consumption in each year. Three of the models (GreenMod II, ISEEM and the Ireland model) introduce Cobb-Douglas preferences for the government, allowing for a simple endogenizing of government consumption.[3] Yet, in actual simulations the ISEEM model resorts again to fixed exogenously government consumption levels, owing to difficulties in solving the model under the Cobb-Douglas government preferences.

It looks that the simplified manner, in which government consumption is modeled, might be partly justified by the purpose of policy-assistance modeling. As actual policy making is done at the government level and many policy measures involve unconstrained changes in government variables, it looks sensible to leave many of them exogenous. Notice, however, that this line of reasoning is weaker in the presence of many branches of government. It seems sensible to restrict policy variables to one branch of government in question, trying to endogenize the behavior of the rest of them.

Finally, we should mention the last item on the expenditure side of

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[3] Recall that the Cobb-Douglas preferences are completely calibrated using only benchmark data: their parameters are equal to the shares of the corresponding consumption products in the total consumption expenditure.

the government budget, i.e., transfers to agents. Most of the models introduce them, though ISEEM and GreenMod II take care to consider unemployment benefits separately. Although "other transfers to agents" (such as pensions) are fixed in these models, unemployment benefits are fixed for each household decile in proportion to the real wages in the corresponding region. This care in modeling unemployment benefits could be explained by particular attention the two models pay to labor issues and, specifically, unemployment.

2.5 Dynamics

The emphasis of early CGE models was on a highly disaggregated static nature of the economy. As a consequence, incorporation of dynamics in this class of models was often done by linking separately solved static models. Even in our relatively modern list of models, dynamics in all but one of them is modeled in this way, commonly known as recursive dynamics. The only model using fully rational forward-looking equilibrium approach is DEAN. A future version of EPPA is also supposed to use forward-looking dynamics.

Dynamic features of any model are driven for the most part by capital formation. As capital and investment data are commonly known on a highly aggregate level, it is necessary to model conversion of ordinary (investment) goods into the new capital. The traditional approach, adopted by all models under review, is to introduce a fictitious firm, which might be industry specific, producing "new capital" out of intermediate inputs. Most of the models assume Leontief production function, whereas two of them (GreenMod II and ISEEM) use the Cobb-Douglas specification. The two models also distinguish between intermediate inputs by region of origin directly in investment production functions. In some models, the distribution of "capital services" of the existing capital stock across industry sectors is also modeled with a fictitious firm with CET (constant elasticity of transformation)[4] production function (DEAN and TEQUILA).

Recursive-dynamic approach prescribes solving static models for each of the time periods and linking them through saving and investment decisions. Savings might be formed by solving the intertemporal consumer problem with some form of adaptive expectations for future prices, or they might directly enter the static utility function and be determined along with the levels of consumed goods solving the static consumer problems (EPPA, GTAP-E and TEQUILA).

Unlike fully-rational forward-looking approach, recursive dynamics does not prescribe a single clear mechanism linking investment and savings in the economy. This leads to several complications, traditionally addressed in model "closures". Thus, the most important question naturally arising in a

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[4] An analogue of the CES production function with several types of output and one input.

recursively-dynamic model is whether investment is essentially determined by savings (EPPA, GTAP-E, TEQUILA), or independently. Three of the models (MMRF-GREEN, GreenMod II and ISEEM) where investment supply is determined independently of savings exploit one and the same approach, based on Dixon and Rimmer (2002).

Recall that in the standard neoclassical theory, supply of *new* capital (i.e., investment) depends on the purchasing price of capital p or, more generally, the cost of installing of new capital, in presence of adjustment costs. Demand for capital is driven by the rental price of capital R (so that it equals the marginal product of capital in the industry). Standard no-arbitrage considerations yield

$$p_t = \frac{R_t + (1-\delta)p_{t+1}}{1+r}, \tag{2.14}$$

where δ is the depreciation rate and r is the interest rate. In the approach espoused in Dixon and Rimmer (2002), the neoclassical no-arbitrage assumption breaks down and investment supply is determined in response to the non-zero expected rate of return ror_t on the newly installed capital. Using our notation, it is easy to see that

$$\mathsf{ror}_t = \frac{R_t + (1-\delta)p_{t+1}}{(1+r)p_t} - 1. \tag{2.15}$$

It is further assumed that the expected tomorrow's purchasing price of capital p_{t+1} is believed to be equal to today's price p_t so that the rate of return is given by

$$\mathsf{ror}_t = \frac{1}{1+r}\left(\frac{R_t}{p_t} - r - \delta\right). \tag{2.16}$$

Notice that the rental price of capital is given by marginal product of capital, whereas the purchasing price of capital without adjustment costs is just equal to the price investment goods.

Finally, investment in new capital is determined as a function of expected rate of return. Specifically, the investment function is implicitly given by the dependence of the expected rate of return on the proportionate growth of capital stock in the industry, according to the inverse logistic function:

$$\mathsf{ror}_t = \mathsf{ror}^{\text{normal}} + \frac{1}{B}\left(\ln\frac{g_t - g^{\min}}{g^{\text{trend}} - g^{\min}} - \ln\frac{g^{\max} - g_t}{g^{\max} - g^{\text{trend}}}\right). \tag{2.17}$$

Here $g_t = K_{t+1}/K_t - 1$ is the growth rate of capital in the industry, $\mathsf{ror}^{\text{normal}}$ is the historically normal rate of return, $g^{\min}$ and $g^{\max}$ are the minimum and maximum allowable growth rates and g^{trend} is the historical industry capital growth trend (corresponding to the normal expected rate of return).

We have already noticed that equation (2.16) determines the expected rate of return. Given that, equation (2.17) determines the capital growth, and hence, tomorrow's level of capital and today's investment.

A slightly different approach is taken by GEM-E3, where investment function is given by

$$I_t = mK_t \left(\left(\frac{R_t}{p_t(r+\delta)} \right)^{\sigma} - (1-\delta) \right), \tag{2.18}$$

where factor m is responsible for the gradual adjustment of capital to the desired level. Disregarding factor m for a moment, notice that this function is set up as if the new capital level $K_{t+1} = I_t + (1-\delta)K_t$ was used as an input in the production of the "desired level" of capital (equal to the actual old level of capital K_t in equilibrium) with a CES production technology with substitution elasticity σ. Notice though, that this analogy cannot be stretched too far, as there are obviously no other inputs in this production process, and they are not accounted for in the SAM.

All of the models that take care of dynamics also strive to account for economic growth. The universal way it is done is through exogenously given efficiency improving factors. Thus, it may be assumed that the same amount of labor input tomorrow will be more productive than today by a given factor. In other words, labor input at period t might enter the production function as $e^{\gamma_l t} l_t$, where γ_l is the growth rate of labor productivity (efficiency). Alternatively or additionally, models introduce total factor productivity growth: the same bundles of inputs produce greater amounts of output, again by a given exogenously factor. Specifically, a production function in period t is not given by a stable function $f(\cdot)$ depending only on inputs, but by $e^{\gamma t} f(\cdot)$, where γ is the total-factor-productivity growth rate.

Special attention is paid to efficiency improvements in energy usage as our models are especially concerned with environmental issues. The corresponding productivity growth factors are called *autonomous energy efficiency improvements* (AEEI) and stand for all non-price driven improvements in technology affecting energy intensity.

Finally, EPPA pays special attention to backstop technologies, e.g., specific technologies that become efficient and are introduced in the economy only with favorable changes in prices. To use such an approach, it is necessary to exploit engineering knowledge on available (though not yet productive enough) alternative technological processes.

All of the models introduce exogenous technological change. Theoretical literature has long since recognized the importance of endogenous, behavioral determination of technical change in the economy. Yet, various difficulties, connected with the nature of generating of new knowledge and accounting for it (either through R&D or learning-by-doing) preclude the development of successful applied models, incorporating endogenous technological growth. For an extensive discussion of this and other issues, connected with economic growth in environmental-economic models, see Löschel (2002).

Finally, the question of managing natural resources is intimately linked to the modeling of dynamics. Two of the models under review (GEM-E3 and EPPA) claim to model depletable natural resources. They introduce the resource in question as an additional input into the corresponding production function. The amount of total reserves is traced through time, and the new reserves each period in GEM-E3 are modeled as a share of the yet-to-be-found reserves emerging according to the rate of discovery. The rate of discovery is given as a function of prices of respective fuels.

Proper modeling of natural resource management calls for the right derivation of changing prices for the resource in the course of its depletion. GEM-E3 finds those prices out of the optimizing behavior of consumers.

3 Environment

The environmental module in a CGE model is built to account both for the influence of economic activity on environment and for the feedback of environmental effects into economy and welfare. The features of environmental modules that modelers have to cope with fall broadly into three categories.

At the very least, all of the models incorporate the accounting of emissions linked to production and consumption. This permits calculation of the disaggregated levels of emissions brought about by economic activity. The introduction of such policy instruments as emission constraints (standards) or emission taxes (treated as adjustments to polluting input prices), as well as energy taxes, allows the models to study their effects on the economy. In the end, economic variables and emission levels, corresponding to the environmental policy in place, can be found and compared with policy objectives.

Many of the models go further and introduce pollution abatement opportunities. The way pollution abatement is modeled varies from model to model and might sometimes seem unnecessarily complicated. The source of complications can be found in the necessity of combining the "bottom-up" approach of estimating abatement opportunities with the "top-down" methodology of CGE modeling. The bottom-up information is derived from the engineering knowledge on available and developing technologies, which often are discrete in nature. In contrast, CGE models strongly prefer continuous production functions that presumably aggregate and smooth the underlying discrete technological features.

Finally, only a few of the models strive to account for feedback effects from the environment back into the economy. It takes the major form of the direct effect on health of individuals (as in the standard GEM-E3, see GEM-E3 (2006)). Further elaborations can also include indirect effects on health through medical expenses and effects on productivity (as in the extension of GEM-E3, introduced in Mayeres and Van Regemorter (2003)).

In this chapter we will explore how the models under review deal with all of the three features.

3.1 Emission accounting

Accounting for emissions is definitely the basic requirement in the environmental CGE modeling, so unsurprisingly, it is present in all of the models under review. Furthermore, the procedures used for emission accounting in all of the models are essentially the same. We might venture a conjecture that the models prefer to banish all possible complications with emission generation into the next category of pollution abatement (see section 3.2).

Emissions coming from fuel combustion, generated by the consumption of each of the sector, are calculated by applying sector- and input-specific emission factors ($\mathsf{ef}_{p,s,i}$) to the corresponding levels of fuel inputs. As those emission factors are usually given for the unit of energy content of the fuel in question, models employ the coefficients of energy content μ_i, given the initial units of the input (usually, in monetary value of the benchmark year). Thus, the emission levels of pollutant p in sector s, corresponding to the combustion of the fuel input i are given by

$$\mathsf{ef}_{p,s,i}\mu_i x_i, \tag{3.1}$$

where x_i is the amount of the input in question. Both emission factors $\mathsf{ef}_{p,s,i}$ and energy content coefficients μ_i are easily available engineering information.

So called process emissions, emanating from the process itself (as in the manufacture of chemicals, agriculture and waste disposal) rather than from a particular input are accounted for by applying a similar fixed factor to the output level of the sector in question (as in EPPA, GreenMod II and MMRF-GREEN).

GEM-E3 goes a step further and tries to account for transport and transformation of emissions. The deposition/concentration levels of pollutants at a given location (region) are calculated, using a simple linear transportation matrix with coefficients standing for the rates of deposition at a receiving location due to a specific source. A linear transformation procedure is used for tropospheric ozone, the pollutant that is formed in atmosphere through photochemical reaction of two primary pollutants, NO_x and VOC, accounted for in the usual way.

3.2 Pollution abatement

Modeling pollution abatement in environmental CGE models turns out not to be straightforward. The reason lies in difficulties of incorporation of the so called “bottom-up” approach, when engineering studies of available and maturing abatement technologies are used for calculating abatement cost functions. By their general nature, CGE models use continuous production functions, presumably given as a result of aggregating various underlying discrete technological processes. The necessity of careful parameterizing production functions corresponding to abatement technologies raises the problem of substituting continuous functional forms for discrete data on available abatement technologies. An alternative approach would be to incorporate discrete technological choices directly into the CGE framework, which might lead to difficulties with the existence of equilibria and their solvability.

Starting from the general methodology of the CGE approach, it seems that ideally, all available abatement technological processes should be incorporated directly into the ordinary production technologies. Consequently, the only two responses to exogenous cost increases in emissions (introduction of ceilings, standards, emission taxes or pollution permits) will be output reduction and substitution of inputs. The latter will account not only for the substitution from pollution-heavy fuels towards less pollution-prone ones, but also for switching-on of various pollution abatement technological processes.

As it stands, environmental issues in the current CGE models call for special attention, including the particular care in incorporating engineering information about available technologies. Thus, the aggregated abatement technologies (through smoothed-out abatement cost curves, for example) tend to be modeled separately from the rest of the production sector in question, but in direct connection with it.

In most of the models (GEM-E3, EPPA, DEAN), the approach to modeling abatement opportunities is basically the same, though the actual implementations might seem different. Thus, GEM-E3 employs the technique of user prices of fuel inputs, whose marginal changes due to changes in the level of abatement determine its optimal level (at least, that is how it is represented in the manual GEM-E3, 2006).

The most transparent and instructive approach is taken by creators of DEAN (see Dellink et al., 2004) on which our following exposition is loosely based. The basic idea is the introduction of the concept of "environmental services", provided to each sector by (fictitious) pollution-abatement firms. By "environmental services" we might understand the output of the "equivalent pollution" that is assumed to go directly into the production function as an input so that it might be bundled in fixed proportions – using emission factors described above – with types of fuels in combustion-related pollution or with the output of a "dirty" production in process-related pollution. By the "equivalent" term we mean that the equivalent pollution is equal to the amount of actual pollution that should have happened in the production of the same output in absence of any abatement technology.

Given this concept, the abatement technology in any production sector is modeled as a process transforming the "numeraire good" and actual pollution as inputs into the output of "equivalent pollution". Finally, for a true CGE model it is necessary to transform the "numeraire good" into actual commodities (which might be taken at fixed shares). Notice, however, that only GEM-E3 mentions the last step in its specification. It is possible to stop the modeling procedure at the level of monetary cost values (the "numeraire goods" as inputs), though in that case the disaggregated values for different inputs in model simulations will be deficient, as they will miss the actual inputs into abatement activities.

The abatement cost curves are mirror images of isoquants of the abatement technology set up in the previous paragraph (see more careful derivation below). Under the CRS assumption, the knowledge of only one isoquant is enough to infer the whole production function.

To be more specific, suppose that $0 \leq a \leq 1$ is the degree of abatement (the share of the retired portion in the total pollution). Define the estimated abatement curve for pollutant p in sector s by $c^{\mathrm{ab}}_{p,s}(a)$ (in line with GEM-E3, 2006). Its value stands for the unit cost of abatement (i.e. the cost of abatement per kg of the initial amount of pollutant). Then the isoquant of the pollution abatement technology, corresponding to the output of environmental services in the amount of 1 unit of equivalent pollution, will be given by the equation

$$m - c^{\mathrm{ab}}_{p,s}(1 - e_p) = 0, \tag{3.2}$$

where m is the "numeraire good" and e_p – the pollution level of pollutant p treated as inputs into the abatement process. Finally, the production function $f(m, e_p)$ of the corresponding abatement technology will be given by the solution f to the following equation:[1]

$$f m - c^{\mathrm{ab}}_{p,s}(1 - f e_p) = 0. \tag{3.3}$$

Given this approach, it is simply the question of estimating abatement cost curves in a "smooth way". DEAN and EPPA do it in such a way that the resultant production function of abatement turn out to be CES. In other words, estimation of abatement cost curves is done with functional forms taken by isoquants of CES functions (see equation (3.2)): the unit cost functions $c^{\mathrm{ab}}_{p,s}(a)$ are fitted by functions of the form:

$$\hat{c}^{\mathrm{ab}}(a) = \left(\frac{1 - \alpha_e^{1/\sigma}(1-a)^{\frac{\sigma-1}{\sigma}}}{\alpha_m^{1/\sigma}} \right)^{\frac{\sigma}{\sigma-1}}, \tag{3.4}$$

with parameters $\alpha_m, \alpha_e > 0$ and $\sigma > 1$.

The creators of GEM-E3 chose a different family of fitting functions. Abatement cost curves there are fitted to

$$\hat{c}^{\mathrm{ab}}(a) = K - \frac{\beta}{1+\gamma}(1-a)^{\gamma+1}, \tag{3.5}$$

where $\gamma, \beta > 0$, K are free parameters. Notice that fitting functions are chosen in such a way that the marginal cost function had the simple form of

$$\left(\hat{c}^{\mathrm{ab}}\right)'(a) = \beta(1-a)^{\gamma}. \tag{3.6}$$

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[1] Recall that the output of the abatement production process is the environmental services in terms of equivalent pollution levels as defined above.

Different approaches to modeling pollution abatement are taken by GreenMod II and MMRF-GREEN. GreenMod II does not consider individual abatement curves, but instead, estimates cost curves of increasing energy efficiency of the production technology in the sector in question, using a special non-integrated microsimulation module. Thus, the information on available and potential abatement technologies is considered not in terms of decreasing pollution given the original fuel-input levels, but rather in terms of the substitution of capital (coming from abatement technology requirements) for the use of polluting fuel-inputs in the production of the same amount of output. In other words, given the model's bundling of all fuel-inputs into the energy bundle, all abatement opportunities are integrated into a new, adjusted CES production function of the capital-energy bundle produced out of capital and energy as inputs.

Notice that given the initial rigid linking of pollution to fuel inputs, no information of abated pollution is lost in this approach (new, lower levels of pollution are arrived at by applying the same emission factors to the new, lower levels of polluting inputs). Moreover, this approach can get much credit as working towards what was described above as the "ideal" solution of integrating abatement technologies into a CGE model. Notice also that this approach grew organically out of the most thorough approach to calibrating elasticities of all the models under review. The sheer prohibiting task of having to specify technologies for 62 sectors and 3 regions in GreenMod II forced its creators to systematically approach the question of its calibration. Obviously, unlike many of the other models under review, GreenMod II could not rely on published information of econometric studies. Hence, the modelers created a special non-integrated microsimulation module, whose task was econometric estimation of technological parameters out of the extensive Belgian data collected by the project team.

To their credit, the GreenMod II creators took great pains to solve an important methodological problem inherent in marrying pollution abatement information with the CGE setting. The unconstrained incorporation of abatement technologies as enhancements to energy usage efficiency typically leads to what is called an "efficiency gap". The new capital-labor bundle technology is necessarily more efficient than the old one (without abatement opportunities). The correct incorporation of the best available technological processes (including the old capital-labor technology) calls for their use in production whenever they remain the most efficient. Thus, the efficiency gap at the benchmark year will be reflected in the new isoquant not being tangent at the benchmarked point to the isocost line, representing the user cost of capital.

GreenMod II solves this problem introducing a sector specific correction factor so that the "corrected" new technology isoquant is tangent to the isocost line, reflecting the required efficiency of the initial, benchmarked, equilibrium. The implicit assumption here is that capital used in abatement and its substitution for energy use has some hidden costs (e.g., due to the uncertainty associated with untested abatement technologies) that are not captured by the user cost of capital, calculated in the conventional way. Those hidden costs are reflected in the introduced correction factor.[2]

Finally, a peculiar approach towards incorporation of abatement opportunities is used in the MMRF-GREEN model. Instead of collecting data on the costs of abatement, this model utilizes the micro data on the actual *levels* of abatement achieved for a given increase in pollution costs (pollution tax). Then technological changes are modeled so that there are adjustments to "technological change" parameters (efficiency coefficients for various fuel inputs). As a result, the tax savings coming from the abatement of pollution, given by fitted micro data, are completely offset by cost increases due to cost-increasing technological change, given the fixed price of polluting inputs bundle (average price of polluting inputs).

Notice that technological change in this approach occurs as adjustment to a change in prices (an increase in taxes). In other words, structurally stable (technological) parameters respond to the movement in prices, which goes against the fundamental nature of any neoclassical economic model. Probably, this way of treating pollution abatement can be traced to the legacy problems plaguing the unfortunate model: MMRF-GREEN creators had to build the environmental module on top of well-established Australian CGE models (MMRF and MONASH).

3.3 Environmental feedback

It is not possible to conduct the welfare analysis of policy measures leading to appreciable environmental effects without calculating monetary values of the environmental feedback into the economy. Among them we can distinguish impact on public health and direct impact on production (through input degradation in, say, agriculture or forestry, or structural damage to buildings, etc.)

The most important of these effects seem to be direct and indirect effects on public health. By the direct effect we mean health deterioration (in both morbidity and mortality dimensions) due to the increase of air concentration of pollutants. Indirect effects include medical expenses incurred by individuals and the decrease in labor productivity.

The only model among those reviewed that attempts to incorporate feedback effects is GEM-E3. At the same time, it limits itself only to direct health effects and some tentative estimations of non-health-related environmental impacts. There is also an extension of EPPA model (EPPA-HE) that claims to include environmental feedback through public

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[2] The discussed earlier approach of accounting for abatement technologies directly faces the same methodological problem, though no other model in our field addresses this issue. All of them implicitly assume that abatement technologies were not available in the benchmark case.

health channels.

Direct health effects calculated in monetary values are usually modeled in the so called "value of life" tradition (see Murphy and Topel, 2006). What is understood by the value of life is the willingness to pay (on behalf of individuals themselves or, possibly, on behalf of the society in presence of altruism) for a small reduction in the probability of dying. Suppose that the utility function of an individual is given in the usual form, separable across time periods and distinct contingencies so that the utility of "being dead" is normalized to 0:

$$\sum_{t=0}^{\infty} \beta^t S_t u(c_{1t}, \ldots, c_{nt}), \tag{3.7}$$

where β is the subjective time-discount factor and S_t is the survival probability of up to time t. The survival probability can be given by $S_t = S_0 S_{t|0}$ where $S_{t|0}$ is the conditional probability of surviving up to period t, given the survival in period 0. Substituting into equation (3.7) and differentiating with respect to S_0 we get that the marginal utility of reducing the probability of dying in period 0 is given by

$$\sum_{t=0}^{\infty} \beta^t S_{t|0} u(c_{1t}, \ldots, c_{nt}). \tag{3.8}$$

Finally, assuming that the first consumption good (c_1) is the numeraire, we get the value of statistical life

$$\mathsf{vsl} = \frac{1}{S_0 u'_{c_1}(c_{10}, \ldots, c_{n0})} \sum_{t=0}^{\infty} \beta^t S_{t|0} u(c_{1t}, \ldots, c_{nt}). \tag{3.9}$$

The naïve application of the value-of-life concept in public health matters might not be appropriate, since there is significant difference between population succumbing to a particular illness (both in morbidity and mortality senses) and general population. Thus, the values of statistical lives estimated for the general population can not reliably be applied in teasing out monetary values of environmental damage on public health. Ideally, the values of lives should be estimated for the population affected, but it is a formidable task for the existing empirical methods. Thus, the study used by GEM-E3 model takes the following shortcut: it infers the approximate value of life of the affected population by using the so-called "value of life years lost" (vlyl), which is the appropriate *constant* average value of years lost of the *general population*:

$$\mathsf{vsl} = \mathsf{vlyl} \sum_{t=0}^{\infty} \beta^t S_{t|0}. \tag{3.10}$$

Under the assumption that the value of life years lost is the same for the affected and general populations, the value of life of the affected population can be found from

$$\widetilde{\mathsf{vsl}} = \mathsf{vlyl} \sum_{t=0}^{\infty} \beta^t \tilde{S}_{t|0}, \tag{3.11}$$

where the survival probabilities $\tilde{S}_{t|0}$ for the affected population are estimated from the data on the number of years lost.

Given estimates of the value of life years lost and epidemiological data on pollutants' impact, it is possible to come up with the monetary value estimate of the direct damage to health, associated with each pollutant. This procedure is employed in GEM-E3.

An extension of the GEM-E3 model, described in Mayeres and Van Regemorter (2003), incorporates not only the direct impact of pollution on public health, but also indirect effects through two additional channels: expenses on medical services and reduction in labor productivity. The top level consumer's utility is now given by the adjusted Stone-Geary preferences:

$$\alpha_1 \ln(c - \underline{c}) + \alpha_2 \ln(l - \underline{l}) + \alpha_3 \ln(h - \underline{h}) - \sum_{p=1}^{m} \alpha_p^{\mathrm{dir}} \mathsf{cl}_p, \tag{3.12}$$

where c is consumption, l is leisure, h is health, cl_p is the ambient concentration level pollutant p, and α_p^{dir} is the marginal disutility of the same pollutant (separable from the direct health effect). Health is given by a simple health production specification:

$$h = h^* - \sum_{p=1}^{m} \beta_p \mathsf{cl}_p + \eta\,\mathsf{med}, \tag{3.13}$$

where h^* reflects the "completely healthy" condition, the coefficient β_p is the constant marginal direct health effect of pollutant p and med stands for expenses on medical services.

The loss of time due to pollution can be captured in the decrease of the available leisure (endowment of labor): $\bar{l} = T - \sum_{p=1}^{m} \theta_p \mathsf{cl}_p$. Finally, the labor productivity loss can be captured in the production function by efficiency coefficients on labor input: efficient labor units will be given by $l\left(1 - \gamma(\mathsf{cl}_1, \ldots, \mathsf{cl}_m)\right)$, where l is the actual labor input and function γ gives the productivity loss due to pollutants.

It is easy to derive the marginal willingness to pay for a reduction in the ambient concentration of pollutant p:

$$\mathsf{mwtp}_p = w\theta_p + p_{\mathsf{med}} \frac{\beta_p}{\eta} + \alpha_p^{\mathrm{dir}} I^d, \tag{3.14}$$

where w are wages and I^d is the "disposable income" (the income net of expenditure on the minimum levels of consumables $\underline{c}$, $\underline{l}$ and $\underline{h}$). All of the three terms in the equation above can be directly deduced from the health-environmental dataset used in GEM-E3 so that θ_p, β_p/η and α_p^{dir} can be estimated. Finally, given these estimates, it is possible to run model simulations and find the exact damage impact of pollution on welfare (see Mayeres and Van Regemorter, 2003).

4 Conclusion

The general and flexible structure, rich features, relatively solid microeconomic foundations, all recommend CGE modeling approach to its employment in policy assistance in complex issues of fiscal policy, international trade, sustainable development and environmental policy. The history of the last several decades, when all flavors of CGE models were successfully deployed in analyzing complex policy issues, confirms this conclusion.

While integrating environmental concerns into the already mature CGE modeling tradition, it has been necessary to reconsider the way industrial sectors were aggregated, allowing for more careful accounting of emissions, both due to combustion of fossil fuels and inherent in the nature of production processes (chemicals, agriculture, waste disposal). The increasing supply of engineering data on available and maturing pollution abatement technologies prompted researches to look for ways in which they could successfully incorporate this useful information in model design. Yet, given the inadequate level of accounting for physical substances in production, a variety of techniques were devised to combat side effects of those deficiencies in modeling sustainable development process. Thus, it seems possible to adjust the existing methodology so as to be able to partially offset such problems as insufficiency of available data, which might be useful in the case of Russia.

This literature review has tried to highlight specific features of actual environmental CGE models in view of the purpose they were serving and the limitations they were facing. Hopefully, this endeavor will help along the ambitious task of constructing a CGE model dedicated to policy assistance in sustainable development issues in Russia.

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