Economic Approaches to Cost Estimates for the Control of Carbon Dioxide Emissions

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Presented at the Sixth Annual Meeting of the European Association of Environmental and Resource Economists, Umeå, Sweden, June 18-20, 1995.

Abstract

This paper gives an assessment of the relative strengths and weaknesses of a variety of economic approaches commonly used for cost estimates for limiting CO_2 emissions, including the *ad hoc* approach, the dynamic optimization approach, the input-output approach, the macroeconomic approach, the computable general equilibrium approach, and the hybrid approach. It illustrates how these different economic approaches are able to shed light on different aspects of the control of CO_2 emissions. Some conclusions with respect to the applicability of each approach are drawn.

Key words: carbon dioxide emissions, computable general equilibrium model, energy, hybrid approach, input-output model, macroeconomic model, optimization model.

Acknowledgement

This study forms part of the ongoing project funded by the Netherlands National Research Programme on Global Air Pollution and Climate Change (NOP). The authors are grateful to the NOP for financial support.

1 Introduction

In recent years, there has been increasing concern about global warming as a result of increased atmospheric concentrations of the *so-called* greenhouse gases (GHGs) and the resulting socio-economic impacts. Although there is a growing consensus in the scientific and policy making circles that climate change and instability are most likely over the next century, there are still uncertainties regarding the magnitude, timing and regional patterns of climate change.

Given the uncertainties and the difficulties in quantifying the benefits from slowing down the rate of climate change through cutting emissions of GHGs, most studies are confined to emission abatement costs and abatement strategies in isolation from their expected benefits, although this may lead to a policy bias towards inaction [7]. Moreover, with carbon dioxide (CO_2) thought to be responsible for half of the present global warming and all GHGs, with the exception of the CFCs, associated with the combustion and/or production of fossil fuels, empirical studies have placed the emphasis on cost estimates for reducing CO_2 emissions from fossil fuels combustion.[1]

Like warming estimates based on the conventional benchmark of a doubling of atmospheric CO_2 concentration from its pre-industrial level, cost estimates for limiting CO_2 emissions also require some common but arbitrary objective to be comparable. Most estimates take as the target a reduction of emissions to either a specified fraction of what they would have been in the absence of controls, or some fixed proportion of the emissions in, say, the year 1990 [32]. The costs of CO_2 abatement are then estimated through the *ad hoc* approach, the dynamic optimization approach, the input-output and macroeconomic approaches, the computable general equilibrium approach, or the hybrid approach. Without going into much detail, this paper attempts to highlight the relative strengths and weaknesses of these different economic approaches. Its

[1] For a survey of empirical studies on the estimates of economic costs for controlling emissions of GHGs, see, for example, Boero *et al.* [15], Dean and Hoeller [8], Hoeller *et al.* [13], and Nordhaus [29].

purpose is to illustrate how these different economic approaches are able to shed light on different aspects of cost estimates for the control of CO_2 emissions, thus highlighting what each approach is best suited to answer.

2 The *ad hoc* approach

The *ad hoc* approach usually comes down to a comparison of a limited number of CO_2 abatement options. Investigating and comparing the cost of specific low-CO_2 technologies, for example, CO_2 scrubbing and substitution of methane for oil and gas, falls into the category. The main purpose of such a comparison is to identify cost-efficient technologies for achieving the specified goals. Alternatively, it allows for ranking the options examined in terms of their cost-effectiveness and hence prioritizes investments in greenhouse abatement.

The approach has been exemplified by a comparison of 15 types of power plants in China in terms of both the levelized cost[2] and the marginal cost of CO_2 reduction at a 10% discount rate. Table 1 shows the results of such a comparison. The results clearly indicate the cost-effectiveness of each plant. The smaller the levelized cost the more cost-effective the plant. This means that renewable energy plants, such as wind and PV plants, are still too costly by comparison with conventional coal and hydro plants, although they can generate electricity without directly parallel production of CO_2 emissions. It is also observed that large coal-fired plants (200 MWe and above) and hydroelectric plants have the negative marginal costs of CO_2 reduction. This implies

[2] Levelized cost spreads total generation cost over total output to arrive at a figure which, if charged for each KWh, would exactly balance costs and income. It was put forward by International Union of Producers and Distributors of Electrical Energy (UNIPEDE) to initially compare cost of nuclear power generation with that of conventional power generation. Afterwards the levelized cost methodology is accepted and widely used by the OECD and the IAEA (International Atomic Energy Agency) nations [37].

that these plants are less expensive than the reference,[3] and should be given to the priority in carbon abatement investments. For a detailed discussion of the results, see Zhang [37].

Table 1 *A comparison of alternative power plants in China*

	Levelized cost (cent/kWh)	Marginal cost[4] (yuan/tC)
Coal power (<200 MWe)	18.995	
Coal power (200 MWe ~ 300 MWe)	16.818	-744.320
Coal power (>300 MWe)	16.248	-602.083
Hydroelectric power (>25 MWe)	14.090	-193.185
Mini-hydroelectric power (≤25 MWe)	14.989	-157.760
Pumped storage hydroelectric power	24.277	208.045
Nuclear power (300 MWe)	29.345	407.627
Nuclear power (600 MWe ~ 1000 MWe)	28.119	359.367
Imported natural gas-fired power	33.179	917.289
Wind-driven power generation	33.034	552.926
Decentralized mini-wind power generator	47.401	1118.777
Centralized solar PV power	118.389	3914.607
Decentralized solar PV power	167.476	5847.905
Biomass-based power generation	31.270	483.448
Geothermal-based power generation	25.109	240.807

Source: Zhang [37].

[3] Coal-fired power of unit capacity of less than 200 MWe is chosen as the reference in our study since it represents a worst case from the point of view of CO_2 emissions. With respect to it, other power supply technologies considered have the potential to reduce a certain amount of CO_2 emissions and are thus regarded as abatement technologies. These abatement technologies are each measured against this reference in terms of both the increased costs and the amount of CO_2 emissions reduced.

[4] In calculating the marginal cost, we use the levelized cost rather than the capital cost. The reason for such a choice is as follows: given that shortages of capital resources are often the main constraint to the adoption of new technologies, the marginal cost of carbon abatement calculated on a basis of capital cost could be useful for policy makers as a means of ranking alternative technologies. Its limitations are also obvious, however, because no account is taken into discounting costs over time, operation and maintenance cost, and fuel cost. This could be likely of a bias towards conventional plants, because advanced plants, though costly, are more energy-efficient compared to the reference.

Given that the costs and timings of alternative options to limit CO_2 emissions differ, the *ad hoc* approach is not well suited to infer the most cost-efficient mix and scale of abatement technologies. Moreover, this approach ignores effects on the national economy.

In what follows, we will focus on the dynamic optimization, traditional economic, computable general equilibrium and hybrid approaches, through which a large number of abatement technologies and activities can be examined in order to identify an optimal mix of technological options and/or to analyze their economy-wide impacts.

3 Dynamic optimization approach

Dynamic optimization models commonly used in the CO_2 context fall into two broad categories. The first refers to energy-sector optimization models [1]. Just as their names imply, energy-sector optimization models, including the widely used MARKAL,[5] focus solely on the energy sector and often have an explicit, detailed description of an extensive array of energy demand and supply technologies and fuels. Upon the representation of these technologies and fuels in a 'shopping list', optimization models simulate the competition among fuels and technologies, and choose the most cost-efficient mix of technologies and fuels to meet the various exogenously determined energy demands and to comply with the emission limits when the minimization of discounted cost over the entire planning horizon is chosen as the objective function.

Energy-sector optimization models are often of an intertemporal structure, and thus allow for interactions between periods. This makes models of this type very useful for assessing the potential of new technologies, especially given the uncertain parameters characterizing these new technologies [2]. Moreover, since models of this type

[5] MARKAL is an acronym for MARKet ALlocation. For a detailed description of the model and some modifications to it, see, for example, Zhang [35,37].

contain great technological detail, they can indicate that much can be done to significantly reduce energy consumption through a wide range of technological opportunities. Thus, they can also be used to look at supply- and demand-oriented policies aimed at curbing energy consumption and hence CO_2 emissions [1].

In modeling the implementation of available technologies, however, energy-sector optimization models consider the possibility of substitution among different options through absolute shifts. Therefore, they risk to underestimate transaction costs and to be too optimistic about potential for market penetration [6].[6] Moreover, although models of this type are able to show how the various exogenously determined energy demands can be met at the least cost, the level of energy services demanded from the energy system is independent of prices. The lack of demand-price interactions is particularly troublesome for models of this type when we anticipate that there will be considerable changes in relative prices caused by CO_2 emission limits [26]. This also rules out the use of models of this type for an estimation of rebound effect.[7] In addition, because models of this type disregard intersectoral linkages (namely, there is no mutual interdependence of the energy sector and the rest of the economy in the models), they have nothing to say about the economic impacts of changes in relative prices caused, for example, by the introduction of a carbon tax.[8] This would lead to incomplete and less reliable assessments and thus seriously flaw the analyses based on

[6] At the consumer level, for example, market failures such as information costs and high discount rates can result in a limited adoption of available options.

[7] The introduction of energy saving technologies does not necessarily lead to a proportionate decrease in energy demand because of substitution and income effect. The rebound effect, which is defined as the ratio of lost energy savings to expected energy savings, just is a means of quantifying this effect. For further discussion, see, for example, Jones [17] and Kram [22].

[8] A carbon tax is an excise tax that is imposed according to the carbon content of fossil fuels. It is restricted to carbon based fuels. It has been shown that if the goal is to reduce CO_2 emissions, a carbon tax is preferred to an energy tax on grounds of cost-effectiveness, because a carbon tax is able to equalize the marginal costs of CO_2 abatement across fuels and therefore satisfies the condition for minimizing the costs of reducing CO_2 emissions. See Zhang and Folmer [38] for further discussion.

such models, in particular when analyzing great changes brought about by a large carbon tax imposed in order to achieve a substantial cut in CO_2 emissions.

The second category refers to those optimization models with a rich treatment of the energy sector but a highly aggregated description of the economy. These models are designed to remove some built-in limitation of the energy-sector optimization models, and at the same time do not get lost in a high degree of technological detail. A good example is ETA-MACRO, which is also called GLOBAL 2100 in order to emphasize both the global nature of the carbon emission problem and also the need for a long-term perspective [25]. It is a merger between ETA (a model for Energy Technology Assessment) and a MACROeconomic growth model with only one final output good in its highly aggregated representation of the economy. In recent modelling efforts, Manne and Wene [26] replace ETA by MARKAL, which has considerably more technological detail than ETA, and link MARKAL and MACRO. Thanks to the simplified representation of the overall economy in MACRO,[9] this linkage is made possible. The linked MARKAL-MACRO model is currently used as an analytical tool of Annex V (Energy Options for Sustainable Development) of the Energy Technology Systems Analysis Programme of the International Energy Agency (IEA-ETSAP) [22].

In either Global 2100 or MARKAL-MACRO, the energy sector links to the rest of the economy in terms of an aggregated nested CES (constant elasticity of substitution) production function, with capital, labour, electric energy and non-electric energy as four inputs. Thus, energy-economy interactions occur via energy inputs to the economy in the production function and inter-industrial payments for energy costs. This makes GLOBAL 2100 and MARKAL-MACRO able to capture price-induced energy conservation and substitution among factors of production for the economy as a whole, thus satisfying macroeconomic policy analysis.

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[9] The treatment makes it less difficult to gather a consistent international data set, while arriving at a meaningful summary of the results. It also lends itself to the interpretation of the results, particularly for long-term projections and economic analysis of energy policies over a century or more on a global scale [12].

As an illustration of the present type of models the MARKAL model and the MARKAL-MACRO model are compared with respect to a reduction of CO_2 emissions by 50% in 2030 relative to the 1990 level in the Netherlands. Figure 1 illustrates how the various steps contribute to reduce CO_2 emissions. The first two steps in MARKAL-MACRO clearly show a reduction of CO_2 emissions by price-induced cuts in GDP growth and specific useful energy demand, which can not be estimated by MARKAL stand-alone. Moreover, the feedback effect of rising energy prices on the specific useful energy demand is subject to the MACRO elasticity of substitution (ESUB) parameter, with a higher ESUB yielding larger decreases in the amount of energy services demanded in MARKAL and hence CO_2 emissions.

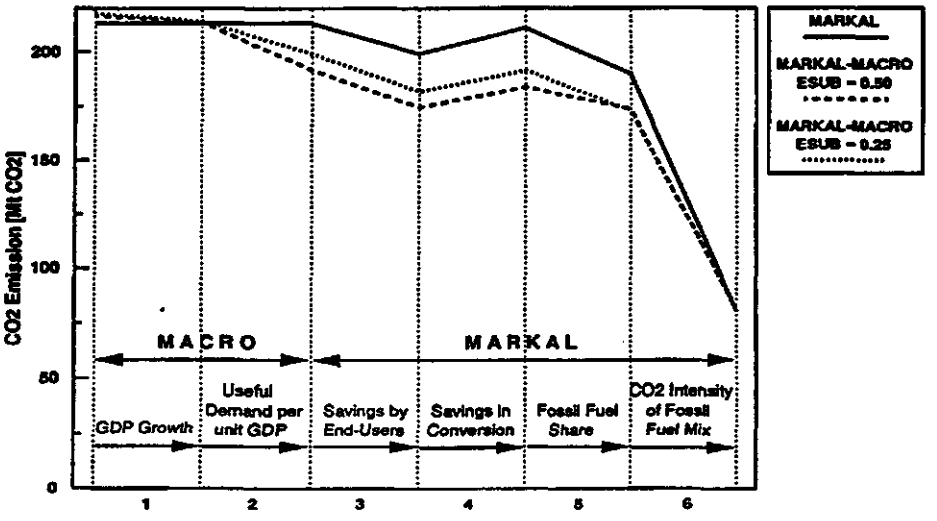

Figure 1 *MARKAL versus MARKAL-MACRO: Steps to reduce CO_2 emissions*

Source: Kram [22].

While Global 2100 or MARKAL-MACRO allows for energy-economy interactions, however, its highly aggregated description of the economy means that neither GLOBAL 2100 nor MARKAL-MACRO can provide detailed information on the impacts of compliance with CO_2 emission limits on individual industries. Thus, this would to some extent limit its value as an evaluation tool for CO_2 constrained policy analysis.

4 Input-output and macroeconomic approaches

In this section, we will discuss two classes of traditional economic models commonly used for the analysis of CO_2 emission limits: a) input-output (I-O) models, and b) macroeconomic models.

The traditional I-O models described systematically the complex sectoral interrelationships in an economy and record the many transactions taking place between the producing sectors of an economy by means of a set of easily solvable simultaneous linear equations. To proceed with environmental policy analysis, the traditional I-O models have been extended to take account of relationships between economic activities and the environment (see, for example, references [28,30] for a further discussion). Less ambitious extensions along this line have involved adding extra rows to represent the generation of pollutants, and sometimes extra columns to represent pollution abatement activities [23,28,30].

In this way, I-O models have been used in a variety of applications, including the analysis of CO_2 emission limits. A good example is the work of Proops *et al.* [31]. It estimates the structural adjustments necessary to achieve a 20% reduction of CO_2 emissions over 20 years (approximately a 1% per annum reduction of CO_2 emissions) for Germany and the UK, using the input-output models for the German and UK economies of 47 sectors. Table 2 shows the results of this calculation, where there are no GDP growth or employment growth constraints. The results suggest that to achieve

Table 2 *Changes in final demand (% change p.a.; -: declines)*

Sector	Germany	United Kingdom
1 Agriculture	-0.17	-0.09
2 Forestry & Fishing	-0.03	-0.01
3 Electricity: fossil generation	0.00	0.00
4 Electricity: other generation	0.00	0.00
5 Electricity: distribution	-2.56	-2.47
6 Gas	-0.02	-0.05
7 Water	-0.01	-0.03
8 Coal extraction, coke ovens, etc	-0.17	-0.05
9 Extraction of metalliferous ores	-0.01	0.00
10 Extraction of mineral oil and gas	0.00	-0.04
11 Chemical products	-1.19	-0.64
12 Mineral oil processing	-0.11	-0.24
13 Processing of plastics	-0.11	-0.04
14 Rubber products	-0.04	-0.03
15 Stone, clay, cement	-0.11	-0.05
16 Glass, ceramic goods	-0.10	-0.04
17 Iron and steel, steel products	-0.60	-0.20
18 Non-ferrous metals	-0.13	-0.09
19 Foundries	-0.02	-0.01
20 Production of steel etc	-0.09	-0.13
21 Mechanical engineering	-0.51	-0.23
22 Office machines	-0.07	-0.02
23 Motor vehicles	-0.77	-0.25
24 Shipbuilding	-0.02	-0.04
25 Aerospace equipment	-0.03	-0.08
26 Electrical engineering	-0.35	-0.20
27 Instrument engineering	-0.05	-0.02
28 Engineers' small tools	-0.17	-0.02
29 Music instruments, toys, etc	-0.03	-0.02
30 Timber processing	-0.02	-0.02
31 Wooden furniture	-0.14	-0.07
32 Pulp, paper, board	-0.14	-0.03
33 Paper and board products	-0.06	-0.03
34 Printing and publishing	-0.02	-0.04
35 Leather, leather goods, footwear	-0.02	-0.02
36 Textile goods	-0.16	-0.08
37 Clothes	-0.08	-0.03
38 Food	-0.92	-0.48
39 Drink	-0.12	-0.14
40 Tobacco	-0.02	-0.02
41 Construction	-0.85	-0.67
42 Trade wholesale & retail	-0.83	-0.84
43 Traffic & transport services	-0.63	-0.64
44 Telecommunications	-0.05	-0.05
45 Banking, finance, insurance, etc	-0.39	-0.22
46 Hotels, catering, etc	-0.28	-0.21
47 Other services	-0.51	-0.07
GDP	-0.57	-0.43

Source: Proops *et al.* [31].

the CO_2 emissions limits would come at the expanse of about half that rate of reduction in GDP in both countries. With respect to the sectoral impact, it is also shown that all sectors are required to reduce final demand, with Electricity Distribution (Sector 5) recording the largest rate of reduction for both Germany (-2.56% p.a.) and the UK (-2.47% p.a.).

I-O models contain a far higher degree of sectoral detail than dynamic optimization model, macroeconomic models and computable general equilibrium (CGE) models to be discussed below, because the computational capabilities of powerful PC's make it possible to solve I-O models with several dozens of sectors without complication and within reasonable time. Consequently, I-O models are most often used where it is important to analyze the detailed sectoral consequences of carbon abatement policies [9]. However, the high sectoral disaggregation of I-O models has its price. To be able to cope with a large number of sectors, I-O models impose a set of strong restrictions, including fixed input-output coefficients, constant returns to scale, perfect factor supply, and exogenously determined final demand. This, in turn, restricts I-O models to short run analysis and means that I-O models paint a somewhat distorted picture of an essentially nonlinear world [9,30].

Now we consider the macroeconomic models. Like I-O models, macroeconomic models are demand-driven. But macroeconomic models go beyond I-O models by carefully modeling the role of prices and by incorporating the supply-side equilibrating mechanisms. Models of this type are neo-Keynesian in spirit in that the final demand remains the principal determinant of the size of the economy and in that macroeconomic models include neoclassical representation of the supply side of the economy. In macroeconomic models, the equilibrating mechanisms work through quantity adjustments rather than price adjustments as in the CGE models. Thus, macroeconomic models allow for temporary disequilibria in the markets for products, labor and foreign exchange, which are represented by the underutilization of production capacities, unemployment, and the imbalance on current account, respectively [4].

There are many macroeconomic models in existence. A good example is the multisectoral HERMES model. It was constructed on behalf of the Commission of the European Communities (CEC) initially for a Harmonized European Research for Macrosectoral and Energy Systems (HERMES), with special emphasis on energy [14]. HERMES has been expanded to accommodate issues surrounding emissions of pollutants, and is used to evaluate the economic consequences of the introduction of a carbon or energy tax.

Table 3 *Main macroeconomic effects in 2005 of the CEC tax*

	Direct taxes	**Social security**	**Public deficit**
1. GDP (percentage deviations relative to baseline)			
France	-0.7	-0.3	-0.92
FR Germany	-0.6	-0.2	-1.37
Italy	-0.0	0.2	-2.19
United Kingdom	-0.7	-0.2	-2.05
Europe 4	-0.53	-0.12	
2. Unemployment rate (percentage deviations relative to baseline)			
France	-0.0	-0.2	0.03
FR Germany	-0.3	-0.7	-0.7
Italy	-0.0	-0.2	0.43
United Kingdom	0.4	-0.1	0.78
Europe 4	0.01	-0.37	
3. Consumer price index (percentage deviations relative to baseline)			
France	4.3	3.2	
FR Germany	2.7	2.0	
Italy	1.8	-0.5	
United Kingdom	5.5	3.1	
Europe 4	3.54	1.92	

Sources: Karadeloglou [19] and Standaert [33].

Table 3 shows the impact of the CEC tax[10] on GDP, unemployment and inflation for the four greatest economies of the EC with the HERMES model, separately and together. The three columns present scenarios under which the carbon tax revenues are retained by the government to reduce public deficit or are recycled into the economy by means of reducing either personal income taxes or employers' social security contributions.[11] It can been seen that the effects of recycling the tax revenues on both GDP and employment are markedly more positive than in the tax retention case and that the macroeconomic effects of reducing social security taxes are less negative than in the direct tax offset case.[12]

It is generally thought that macroeconomic models are often more related to reality than CGE models to be discussed below, because a number of interrelated equations in macroeconomic models are determined by the traditional econometric approach, which relies largely on reliable time-series data for sufficiently long periods [15,27]. Consequently, these models are able to capture the transitional impacts of exogenous shocks caused, for example, by the introduction of a carbon tax on such main economic indexes as inflation and unemployment, which are crucial and dominate the decision-making process in particular in the short run [3]. This makes macroeconomic models a persuasive instrument in influencing decision-making [9]. According to the Lucas critique, however, in making forecasts macroeconomic models use fixed estimates of relationships that held in the past but may be altered by the change in policy, and if this is the case then the estimated effects of the change will be incorrect [24]. Clearly, this critique indicates that macroeconomic models are an inappropriate tool for analyzing the economic effects of large

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[10] As part of its comprehensive strategy to control CO_2 emissions and increase energy efficiency, a carbon/energy tax has been proposed by the CEC. The CEC proposal is that member states introduce a carbon/energy tax of US$ 3 per barrel oil equivalent in 1993, rising in real terms by US$ 1 a year to US$ 10 per barrel in 2000. After the year 2000 the tax rate will stay at US$ 10 per barrel in 1993 prices. The tax rates are allocated across fuels, with 50% based on carbon content and 50% on energy content [38].

[11] Although the non-environmental dividend of a carbon tax is very often interpreted as using the extra carbon tax revenues to reduce existing distortionary taxes for raising government revenues, it can of course have other interpretations. For instance, reduced unemployment is referred to as the potential extra dividend in addition to improved environmental quality [38].

[12] This highlights that the 'double dividend' feature of a carbon tax has important implications for 'green tax swaps' for distortionary taxes. For further discussion, see, for example, Zhang and Folmer [38].

changes in the demand and/or supply structure of an economy and those questions of long-run nature. This weakness limits their applicability to the analysis of a large carbon tax, because the short-run focus of macroeconomic models does not coincide with the time required for a carbon tax to materialize and because their usefulness in analyzing the effects of 'small' carbon taxes by no means guarantees their reliability in the analysis of large carbon taxes required for achieving a substantial cut in CO_2 emissions, say, the Toronto target.

5 Computable general equilibrium approach

An environmental policy aimed at curbing CO_2 emissions by a means of a carbon tax will change the relative prices of goods. Carbon-free or low-carbon containing goods and services become cheaper than those of high carbon-intensity. Such changes in the relative prices will lead to shift away from high-carbon energy, away from energy towards capital and labor, and away from carbon intensive goods and services. This will have feedback effects on the economic structure and products mix, economic growth, the allocation of resources, and the distribution of income. Clearly, analyzing such economy-wide impacts can not be carried out within a partial equilibrium framework. Moreover, if the carbon taxes are used to achieve, for example, the Toronto target, they must be non-marginal and therefore cannot be estimated reliably by partial equilibrium approaches, I-O models or macroeconomic models, which can at best indicate the effects of 'small' carbon taxes. Thus, CGE models are called for.

Indeed, from a theoretical point of view, CGE models are preferred to I-O models and macroeconomic models, because CGE models are based on solid microeconomic foundation. In CGE models, the behaviour of economic agents is modelled explicitly and is based on microeconomic optimization principles, whereas macroeconomic models pay less attention to economic theory and more attention to time-series data [15]. CGE models often operate by simulating the operating of markets for factors, products and foreign exchange, with equations specifying supply and demand behaviour across all markets, and are endogenously solved for a set

of equilibrium wages, prices and an exchange rate to clear these markets [37]. CGE models are Walrasian in spirit in that the equilibrating mechanisms work through changes in relative prices. The equilibrium solution to CGE models produces a wealth of detailed information, including market clearing prices and quantities for sectoral output, investment, employment, foreign trade, energy consumption and CO_2 emissions.

If macroeconomic models pay specific attention to modelling transitional adjustment costs associated with policy changes or exogenous shocks, CGE models place emphasis on examining the economy in different states of equilibrium instead. Recognising that it can take considerable time for prices to adjust to bring supply and demand back into equilibrium, CGE models are essentially long-run in conception [9,15]. Moreover, in CGE models, parameters in utility functions and production functions are structural parameters, representing tastes and technologies. This makes CGE models less vulnerable to the Lucas critique [20]. Further, CGE models include a government sector, so the effects of alternative means of recycling the revenues generated by carbon taxes can be analyzed.

From the preceding analysis, it is not surprising that CGE models are widely used to analyze the economic effects of limiting CO_2 emissions, both at the national level and at the international level.[13] As an illustration of national CGE models, Table 4 gives the main macroeconomic results for China of the introduction of carbon taxes, which are obtained with the time-recursive dynamic CGE model for energy and environmental policy analysis of the Chinese economy.[14] In Scenario 1 a carbon tax is imposed at a level of 230 yuan per ton of carbon (tC) in order to achieve about 20% cut in CO_2 emissions in 2010 relative to the baseline, whereas Scenario 2 considers a case of the introduction of a carbon tax of 440 yuan/tC in order to achieve about 30% cut in CO_2 emissions in 2010. Comparing the levels of carbon taxes under the two carbon constraint scenarios shows that the larger absolute cut in CO_2 emissions will require the higher carbon tax. The higher tax also implies the higher fuel-specific tax rates because the carbon

[13] For both national and international examples, see, for example, the references in Zhang [36,37].

[14] For a detailed description of the CGE model and its application, see Zhang [37].

tax becomes larger relative to the baseline prices of fossil fuels. As a result, the larger increase in the prices of fossil fuels occurs in Scenario 2 than in Scenario 1, compared to the baseline. Moreover, carbon tax rises at an increasing rate as the target of CO_2 emissions becomes more stringent, indicating that large reductions in carbon emissions can only be achieved by ever-larger increases in carbon taxes.

Table 4 *Main macroeconomic results for China of the introduction of carbon taxes in 2010* (percentage deviations relative to the baseline; +: increases; -: declines)

	Scenario 1	Scenario 2
Volumes		
GNP	-1.546	-2.810
Welfare[a]	-1.120	-1.814
Private consumption	-1.222	-3.052
Investment	-0.627	-1.781
Exports	-5.453	-7.551
Imports	-1.171	-2.158
Energy consumption	-19.400	-28.923
CO_2 emissions	-20.225	-29.876
Prices		
Price of coal	72.713	135.011
Price of oil	17.230	32.207
Price of natural gas	52.591	99.795
Price of electricity	25.591	47.636
Terms-of-trade	3.697	3.901
Prices of exports	3.692	3.879
Prices of imports	-0.004	-0.022

[a] Measured in Hicksian equivalent variation.

Source: Zhang [37].

With respect to the volume effects of carbon taxes, the results in Table 4 show that China's GNP and all its components as well as welfare in 2010 are negatively affected under the

two CO_2 constrained scenarios compared to the baseline. Exports constitute the final demand category that is reduced the most. Given the exogenous current account constraint, a decline in export volumes plus a rise in export prices also makes import volumes fall less than export volumes. Moreover, with the terms-of-trade improvement that tends to offset the deadweight losses arising from the imposition of carbon taxes, household real income i.e. welfare that is measured in Hicksian equivalent variation falls less than GNP. As can also be seen, the associated falls in GNP and welfare rise as the carbon emission targets become more stringent. Moreover, it is indicated that the falls in GNP and welfare tend to rise more steeply as the degree of the emission reduction increases. Put another way, the economic costs of incremental environmental policy actions increase with the level of the emission reduction. This is reflected by, for instance, the increased elasticity of welfare with respect to emission reduction, which is 0.056 at about 20% required rate of carbon reductions, and 0.061 at about 30% required rate of carbon reductions. This increasing marginal cost of emission reduction implies that further reductions in CO_2 emissions are becoming significantly more difficult. This finding also corresponds to other CGE studies; see e.g. references in Zhang [36,37].

CGE models have, of course, some limitations for practical policy decisions. The most frequently mentioned one is the lack of empirical validation [3]. Although there are some exceptions, most CGE models are calibrated rather than econometrically estimated.[15] The calibration procedure often borrows a variety of elasticities from other studies. Whatever values of elasticities are eventually chosen, they are difficult to defend, because often these studies do not contain the same definitions of variables or level of disaggregation. The second weakness is related to the general equilibrium assumption. This assumption, combined with that CGE models stress relative prices,[16] rules out the use of CGE models for analyzing traditional disequilibrium

[15] Among the examples adopting the traditional econometric approach to CGE modeling are the DGEM model for the United States [18] and the work of Glomsrød *et al.* [10] for Norway.

[16] All supply and demand functions in CGE models that are mainly used for the allocation of resources are assumed to be homogeneous of degree zero in prices. As a consequence, only relative prices are important for the determination of the quantities of goods supplied and demanded. Thus, CGE modellers usually choose a price index as the price numéraire, and all other prices are measured relative to it. Although any price index could be used as the price numéraire, common choices in CGE models are the GNP (GDP) deflator, a consumer or producer

issues such as inflation and unemployment [3,15]. Another limitation built into most CGE models is the adoption of perfect competition assumption.[17] Clearly, this is not representative of the real world in which many cases of market failure exist, such as monopoly power and imperfect competition [9,15].

6 Hybrid approach

As discussed earlier, bottom-up models[18] like energy-sector optimization models take a disaggregate approach to modelling energy supply and demand [34]. They can identify, for example, the potentials of energy efficiency improvement to which each energy technology will contribute, and provide information on the corresponding costs required to achieve such potentials. In bottom-up models, however, the transaction costs associated with implementing technologies and the feedbacks from and to other sectors of an economy are not included. By contrast, top-down models such as macroeconomic models and CGE models take a macroeconomic approach to modelling energy-economy interactions and the costs of changing them [34]. They can provide detailed information on the impacts on individual industries. But in top-down models, future energy demand and the cost of changing it are to a large extent determined by two macroeconomic parameters, which are respectively known as autonomous (i.e. non-price-induced) energy efficiency improvement and the elasticity of price-induced substitution between the inputs of

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price index, the exchange rate, or the wage [37].

[17] In principle, this weakness can be overcome. To cite an example, Harris [11] introduces economies of scale in production and imperfect competition in an applied general equilibrium model for the analysis of trade liberalization. But the example remains an exception in the sense that it has not had many followers among CGE modellers. The reason would be that incorporating economies of scale and imperfect competition into CGE models, though useful for a policy study based on a CGE model, would complicate the analysis. Thus, for simplicity, a number of CGE modellers adopt the explicit assumption of constant returns to scale in production and perfect competition.

[18] The *so-called* bottom-up models refer to those models that typically incorporate a detailed representation of technologies for energy supply and use, but little representation of markets and none of the rest of the economy. Thus, these models are often referred to as the engineering models.

capital, labor and energy and which are neither physically observable nor measurable [34].[19] Consequently, it is impossible for top-down models to indicate from where energy conservation originates and to convince energy planners how it can be achieved.

Given the relative strengths and weaknesses of bottom-up models and top-down models, these two approaches, rather than competing or substituting, can certainly complement each other if they are linked together. Because of operational difficulties in directly linking models of the two types, less ambitious attempts in this direction have involved informal linkage between the existing bottom-up model and top-down model. The purpose of such linkage is to establish a consistent interaction between these two models, thus shedding light on both economic and technological aspects of the control of CO_2 emissions. Clearly, results based on this approach can satisfy both *environmental policy analysis and energy planning requirement*.

In informally linked system, these two models are operated as parallel independent units but the results from one model run can be reflected in the other model to arrive at consistent scenarios for economic development, fuel choice, cost-efficient mix of energy technologies, and CO_2 emissions. The implementation following this approach has been exemplified by an early study, which integrates MENSA, an Australian regionlized version of MARKAL, with an Australian input-output model MERG [16]. In the informally linked MENSA-MERG system, MENSA aims to define the most efficient structure for the allocation of fuels to the various end-use sectors. The evolution of structural shifts in the energy system exhibited in the MENSA solution would then be reflected in the MERG model as time-dependent intersectoral energy coefficients. These in turn would modify the end-use demands for energy within MENSA. Thus,

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[19] The first parameter accounts for all but energy price-induced energy conservation. Energy conservation of this type is avaiable at zero or negative net cost. In cost-benefit analysis of greenhouse gas control, this implies, *ceteris paribus*, a higher optimal level of emission reduction than the case where abatement costs are always positive. Energy conservation of this type is taking place regardless of the development of energy prices. It may be brought about by regulations. It may also occur as a result of 'good housekeeping' or a shift in the economic structure away from energy-intensive heavy manufacturing towards services. In the case where the parameter lowers the rate of growth of CO_2 emissions over time, and therefore decreases the amount by which CO_2 emissions need to be constrained, the economic impacts of a given carbon constraint will also be lower. The second parameter serves as a factor measuring the ease or difficulty of substitution for energy during a period of rising energy prices. Thus, energy conservation of the second type occurs as a reaction to rising energy prices [37].

the calculations would proceed iteratively until some convergence criterion was satisfied. Recent examples in this tradition are the ongoing work of various IEA-ETSAP member countries, which is performed to link a member country version of MARKAL with a macroeconomic model of its own [21]. In this way the energy and environmental effects can be addressed in relation to the macroeconomic effects.

If bottom-up model is a simplified energy model, a direct linkage is possible.[20] A good example is the linked HERMES-MIDAS model [5]. This linkage occurs by eliminating energy equations from HERMES and macroeconomic equations from MIDAS (Multinational Integrated Demand And Supply), which is a country-specific energy demand and supply model developed for European countries under the auspices of the CEC. Unlike the linkage between MENSA and MERG that is mentioned above, the linked HERMES-MIDAS model is considered a single model since the linkage has been constructed to be formal and numeric by means of interface modules performing transformations of linked variables. This linked model has been used to evaluate the economic consequences of the introduction of a carbon or energy tax on both the economic and energy system for the four greatest economies of the EC [19].

While a hybrid approach is able to shed light on both economic and technological aspects of the control of CO_2 emissions, however, it does have drawbacks. In order to obtain consistent linking results, a hybrid approach needs to remove all the inconsistencies built into the two models. This often turns out to be cumbersome and time-consuming. Moreover, top-down models are very different from bottom-up models in terms of the discipline from which they originate, which reflects that each modeller approaches the cost estimates for the control of CO_2 emissions starting with the best understood aspects, so a hybrid approach presents an additional requirement for cooperation between modellers of different disciplines.

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[20] As discussed in Section 3, directly linking a simplified top-down model with a complicated bottom-up model has been exemplified by MACRO-MARKAL.

7 Conclusions

From the preceding analysis, we draw the following main conclusions. First, if focus is primarily placed on technological solutions to CO_2 emission problems, dynamic optimization models are very useful. Moreover, in order to prioritize investments in carbon abatement technologies, specific cost-effective analysis for these technologies is helpful. In this respect the *ad hoc* approach may be used. Second, of a variety of models discussed in this paper, none contains more sectoral detail than input-output models. Therefore, if interest centres mainly on the consequences of a carbon tax on the economic structure, input-output models are generally considered an appropriate tool for such a purpose. Third, the transitional impacts of a carbon tax on inflation and unemployment can best be captured in macroeconomic models. Thus, if focus is placed on an estimation of transitional adjustment costs in the short-run, we can rely on macroeconomic models. Fourth, CGE models are an appropriate tool for analyzing the economic effects of large changes in the demand and/or supply structure of an economy and those questions of long-run nature. If we want to shed light on long-run aspects of a large tax imposed for achieving a substantial cut in CO_2 emissions, CGE models are called for. Finally, given the relative strengths and weaknesses of bottom-up models and top-down models, it is worthwhile linking them together and serving to complement each other, thus shedding light on both economic and technological aspects of the control of CO_2 emissions.

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