Global 2100: An Almost Consistent Model of CO_2 Emission Limits

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I. INTRODUCTION AND SUMMARY OF RESULTS

This paper describes Global 2100, an analytical framework for estimating the costs of carbon emission limits. The model is designed to evaluate CO_2-energy-economy interactions. The analysis is based upon *parallel* computations for five major geopolitical regions: the USA, other OECD nations, the USSR and Eastern Europe, China and ROW (rest of world).

The name Global 2100 has been adopted in order to emphasize both the global nature of the carbon emissions problem and also the need for a long-term perspective. There are long time lags inherent in the buildup of CO_2 and in the transition away from carbon-based fuels. The model is benchmarked against 1990 base year statistics, and the projections cover ten-year time intervals extending from 2000 through 2100. This is an intertemporal rather than a recursive system. It is assumed that producers and consumers will be sufficiently farsighted to anticipate the scarcities of energy and the environmental restrictions that are likely to develop during the coming decades. In this respect, it represents an advance over the recursive model adopted by EDMONDS and REILLY (1985), the pioneers in global CO_2 analysis.

For each region, a dynamic nonlinear optimization is employed to simulate either a market or a planned economy. Supplies and demands are equilibrated within each individual time period, but there are "look-ahead" features to allow for interactions between periods. These interactions are particularly important for the depletion of exhaustible resources and for the accumulation of capital over time. Savings and investment decisions are modeled through the maximization of discounted utility. Con-

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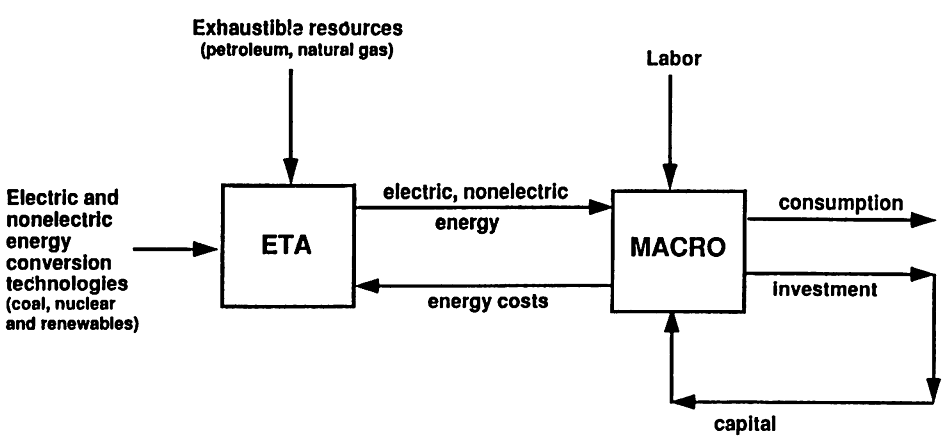
The following numerical results are excerpted from two joint papers with RICHARD RICHELS (1990a) and (1990b). The views presented here are solely those of the individual authors, and do not necessarily report the views of EPRI or its members.

sumers will therefore receive equal benefits from an additional dollar's worth of current consumption and a dollar's worth of investment.

In order to decompose the overall problem into more manageable subproblems, it is supposed that each of the five regions faces an exogenously determined carbon emissions quota and an international crude oil price. The model is *almost* consistent. That is, it neglects the possibility that carbon emission rights may be sold from one region to another. It also neglects the possibility that the international oil price is set too high or too low. Alternative scenarios (informal iterative methods) are employed to eliminate the prospective gaps between oil supplies and demands. In its present form, the model provides useful insights. At some point, however, it would be instructive to extend the formulation to include those features which can only be handled through an applied general equilibrium model.

Within each region, the analysis is based upon ETA-MACRO, a model of two-way linkage between two submodels. One is ETA (an energy technology assessment model), and the other is MACRO (a macroeconomic production function describing the balance of the economy). (See *Figure 1.*) Energy *supplies* include both exhaustible hydrocarbon resources and also "backstop" technologies. Associated with each of the supply technologies, there are coefficients describing the costs and the carbon emissions per unit of the activity level. There are upper bounds upon the speed of introduction of new technologies and lower bounds upon rates of decline.

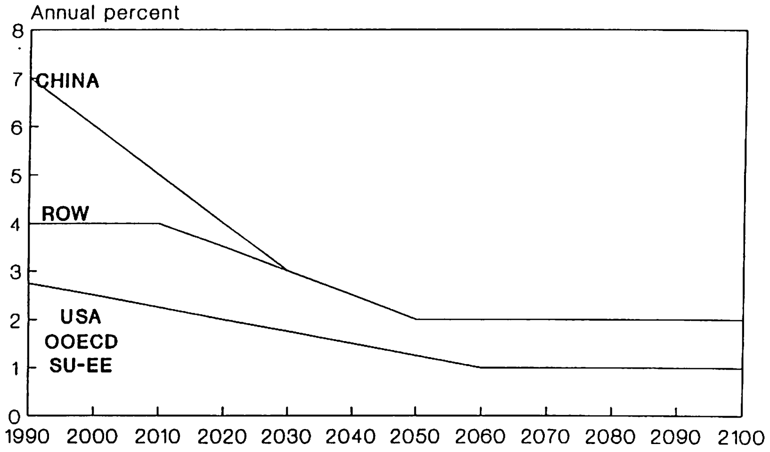
Figure 1: Overview of ETA-MACRO



In order to avoid the data-intensive approach that is associated with an end-use analysis, energy *demands* are divided into just two categories: electric and nonelectric. Along with capital and labor, energy is viewed as a basic input into the economy-wide macro production function. The growth rate of the labor force (measured in 'efficiency units') may also be described as the *potential* rate of GDP growth within each region. (See *Figure 2*.) These rates constitute one of the key inputs into the model.

Energy consumption and carbon emissions need not grow at the same rate as the GDP.

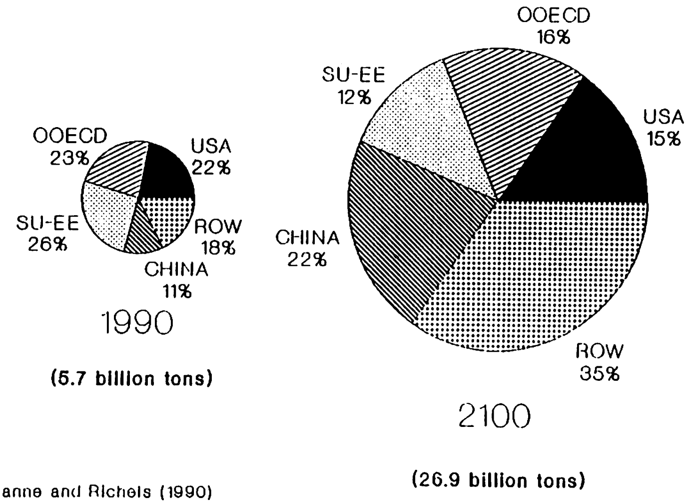
Figure 2: Potential GDP Growth Rates



Over the long run, they may be decoupled from GDP growth. In ETA-MACRO, these possibilities are summarized through two parameters. One is termed AEEI (autonomous energy efficiency improvement), and the other is ESUB (the elasticity of price-induced substitution between energy and other productive inputs). One example of AEEI (costless improvements) would be those that are automatically induced by changes in the structure of the economy away from manufacturing and toward the service sector. Another example might be government standards for energy efficiency improvements in the case of those items for which consumers lack the relevant information or the capital to adapt to cost-effective changes. In a period of rising international oil prices, both price and non-price-induced conservation will permit a significant reduction in carbon emissions. Under the reference case assumptions, however, they are not sufficient to stabilize total primary energy demands. Additional supply sources are needed – both in the electric and nonelectric sectors.

Through 2010, the combination of conservation and increased reliance on natural gas may be sufficient to achieve a balance between supplies and demands. Beyond 2010, low-cost hydrocarbon resources are likely to prove inadequate, and new supply options will be required. For the electric sector, we have assumed an advanced low-cost carbon-free backstop (abbreviated ADV-LC). This could be, for example, either nuclear or photovoltaics. For the nonelectric sector, it is supposed that two backstops are available – SYNF (coal or shale-based synthetic fuels) and also NE-BAK (a nonelectric backstop, e.g., biomass-based fuels). SYNF has lower costs but much higher carbon emissions than

Figure 3: Unconstrained Carbon Emissions Scenario

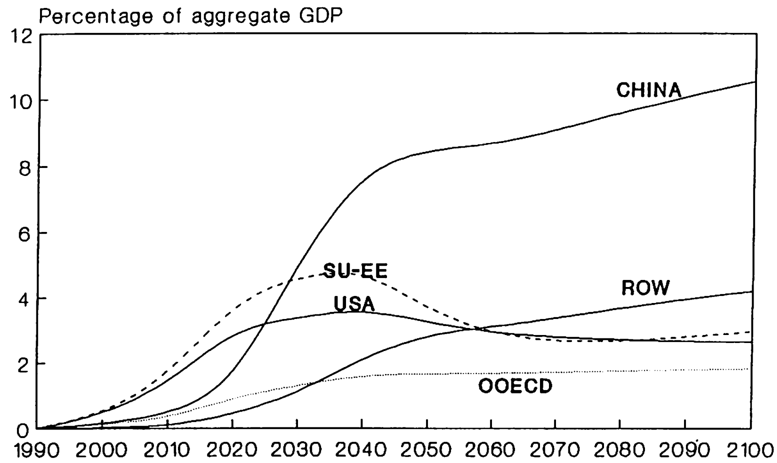


NE-BAK. *Figure 3* illustrates how carbon emissions might grow under these supply and demand assumptions.

There are many possible ways of defining a global agreement on carbon emission limits. To illustrate these ideas, it is useful to consider a scenario in which the OECD countries, the Soviet Union and Eastern Europe each agree to stabilize carbon emissions between 1990 and 2000, and then reduce them gradually by 20% in 2020. In return, China and ROW would limit their growth in emissions to a 100% increase above 1990 levels. Overall, this proposal would lead to a 15% increase in global emissions between 1990 and 2020, but no further increase thereafter.

Under these assumptions, the costs of a carbon emissions limit remain low through 2000, but the emissions reductions are also low. Beyond that date, the costs become significant. In percentage terms the GDP losses look small, but they are comparable to the amounts that are now being devoted to the U.S. military budget. (See *Figure 4*.) The costs are particularly high in the case of China – a country that is richly endowed with

Figure 4: Losses Due to Carbon Limit



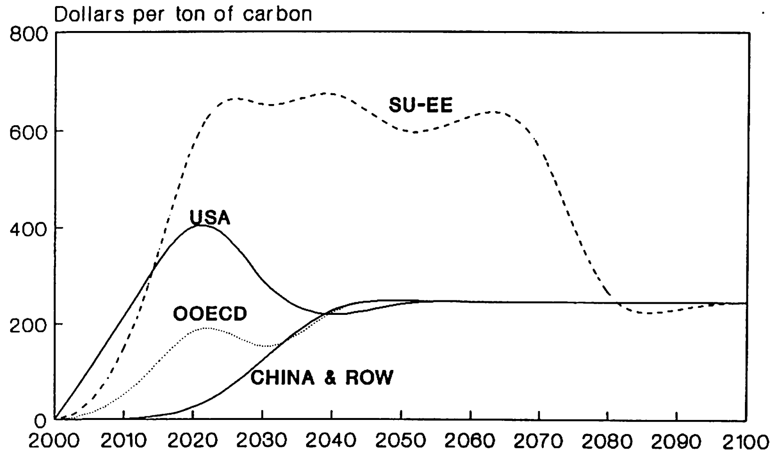
Source: Manne and Richels (1990)

coal, but not with hydrocarbon resources. It would be quite expensive to shift from a coal-based economy to one that is based upon land-intensive renewables.

Within each region, it is assumed that policies will be designed so as to achieve an optimal allocation of emissions between the electric and nonelectric sectors. For a market economy, these allocations could be achieved through a uniform carbon tax. *Figure 5* compares the region-by-region time paths for the carbon tax that are implicit in this international scenario. The specific path depends upon one's assumptions with respect to both supply and demand factors. The higher the value of the ESUB and AEEI parameters, the less expensive it becomes to reduce energy consumption. The lower the costs and the more rapid the maximum expansion rates for new supply technologies, the smoother becomes the transition to a low-carbon scenario.

In typical runs, it turns out that the long-run equilibrium level of the carbon tax is the amount required to equalize the price that consumers would have to pay for NE-BAK and for SYNF. The size of the tax is determined by the cost difference between NE-BAK and SYNF divided by the difference in their carbon emissions coefficients. For example:

Figure 5: Carbon Taxes



Source: Manne and Richels (1990)

$$\frac{\text{Cost differential, \$/million BTU}}{\text{Carbon differential, tons/million BTU}} = \frac{\$20 - \$10}{.04\text{ tons}} = \$250/\text{ton of carbon.}$$

In the U.S., a carbon tax of $250/ton would imply a five-fold increase in the price of coal – or an increase of $.75/gallon of refined petroleum products. If one region were to sell just 100 million tons of carbon emission rights to another region, this tax rate would imply a net financial transfer of $25 billions!

The price of oil does not have a major impact upon carbon emission scenarios. However, because the carbon emissions coefficient of oil is only half that of synthetic fuels, carbon emission limits *could* affect international oil prices. In the presence of carbon constraints, conventional oil enjoys a premium value relative to coal and shale-based synthetic fuels. In the short term, carbon limits could reduce the demand for oil. Over the long term, however, carbon limits will strengthen the market power of OPEC. In the absence of carbon limits, synthetic fuels impose a relatively low cap on the international price of oil, e.g. $10/million BTU – that is, $60/barrel. With carbon emission limits, there is a premium on oil relative to synfuels, and a higher international oil price is required in order to balance supplies and demands. If a carbon-free backstop costs \$20/million BTU (\$120/barrel of crude oil equivalent), the international price of oil could rise to \$90/barrel.

Global 2100 is not designed to provide a quantitative analysis of the patterns of international trade. Even without such an analysis, it is clear that there would have to be an international market in emission rights, or else there could be a profound impact of carbon quotas upon the division of labor. Emission limits would affect the comparative advantage of individual regions in the production of carbon-intensive commodities such as steel. Unless the newly industrialized countries (Brazil, China, India, Mexico and South Korea) agree to fairly stringent emission limits, they could become major steel exporters to the OECD and to other nations. These changing patterns of trade could well have a perverse impact upon global carbon emissions. To analyze these issues, additional applied general equilibrium work is needed along the lines suggested by WHALLEY and WIGLE (1989).

II. FORMULATION OF SINGLE-REGION MODEL - SETS, VARIABLES AND DATA TABLES

Global 2100 is written in GAMS (a generalized algebraic modeling system). See BROOKE et al. (1988). In order to solve two cases (with and without a carbon constraint) for all five regions, it requires about 20 minutes on a 25 Mhz desk-top 386 computer equipped with a coprocessor. With the GAMS language, it is natural to begin by describing the sets, then the decision variables and data tables. The sets are as follows:

ET	Electric energy supply technologies: /HYDRO,GAS-R, OIL-R,COAL-R, NUC-R, GAS-N, COAL-N, ADV-HC, ADV-LC/
NT	Nonelectric energy supply technologies: /OIL-MX, CLDU, OIL-LC, GAS-LC, OIL-HC, GAS-HC, SYNF, NE-BAK/
X	Exhaustible hydrocarbon resources: /OIL-LC, GAS-LC, OIL-HC, GAS-HC/
DL	Electricity technologies subject to decline limits: /GAS-N, COAL-N, ADV-HC/
EX	Electricity technologies subject to expansion limits: /ADV-HC, ADV-LC/
NX	Nonelectric technologies subject to expansion limits: /SYNF, NE-BAK/
GS	Natural gas supply and demand technologies: /GAS-R, GAS-N, GAS-LC, GAS-HC/

Among the decision *variables*, the maximand UTILITY is a scalar. All other variables are time-indexed, and refer to the projection periods $t = 1$ (2000), 2 (2010), . . . T (2100).

Base year values of all variables are denoted by $t = 0$ (1990). The list of variables is as follows:

UTILITY	Sum of discounted logarithms of aggregate consumption

Units of measurement for the following variables are $ trillions per year:

C	Consumption
I	Investment
EC	Energy costs
Y	Production, excluding energy sectors
YN	New vintage production, excluding energy sectors

Units of measurement for the following variables are $ trillions:

K	Capital stock
KN	New vintage capital

Units of measurement for the following variables are TKWH (trillion kilowatt-hours) per year:

E	Demand for electric energy - before AEEI
EN	New vintage demand for electric energy
PE	Supply of electric energy-members of the set ET
XPE	Above-normal expansion of electric energy-members of the set EX

Units of measurement for the following variables are quads (quadrillion BTU) per year:

N	Demand for nonelectric energy – before AEEI
NN	New vintage demand for nonelectric energy
PN	Production of nonelectric energy-members of the set NT
XPN	Above-normal expansion of nonelectric energy-members of the set NX
GN	Gas consumed to meet nonelectric energy demands
RSV	Proven reserves
RSC	Undiscovered resources

Units of measurement for the following variables are billion tons of carbon per year:

DC	Quantity of carbon deferred from use in period t and available in period t+1.

Bounds on individual variables:

The variables UTILITY and EC are allowed to take on negative as well as positive or zero values. Except for these variables, *lower* bounds are imposed upon all others. The lower bounds help to reduce the solution time and/or to prevent program calls for undefined numbers, e.g. for the logarithm of zero. These lower bounds are intended to be non-binding constraints at an optimal solution.

Upper bounds are imposed upon the variables PE and PN through the data tables ECAP and NCAP, respectively. There are additional upper and lower bounds on individual PE and PN variables:

Hydroelectric production is *fixed* at the values shown in the ECAP table.

The CLDU (coal - direct uses) variables are subject to a lower bound determined by their base year level and an upper bound determined by this initial level, the potential GDP growth rates and the CLGDP elasticity specified in the MACRO table.

The OIL-MX (oil import-export) variables are subject to the lower and upper bounds specified in the tables OILM and OILX. The ROW (rest of world) region includes OPEC. For this region, there is an additional bound on exports – the net demands generated by the USA and other OECD countries less the amounts supplied by the Soviet Union-Eastern Europe and China. This means that the ROW solution must be calculated *after* those for the other four regions.

In formulating the constraints, all parameters have been indicated by lower-case letters. These values are specified either directly or indirectly through a series of data tables which the user is free to modify. For example, the MACRO table contains the region-by-region values for *gdpo* (the initial GDP), *kgdp* (the initial capital-GDP ratio), *kpvs* (capital's value share), and *depr* (the annual depreciation rate). The potential GDP growth rates ($grow_t$) are contained in the GROW table, etc. All input data are grouped into the following files:

MACRO:	MACRO	Macroeconomic and other parameters
	GROW	Potential GDP growth rates
	AEEI	Autonomous energy efficiency improvements
OILTRADE :	OILP	International oil price scenarios
	OILX	Oil export limits
	OILM	Oil import limits
ELEC:	ECAP	Electricity production capacities
	ECST	Electricity cost coefficients

NELE:	NCAP	Nonelectric production capacities
	NCST	Nonelectric cost coefficients
	SDAT	Supply data - exhaustible hydrocarbon resources
CARBON:	CH	Carbon emission coefficients and heat rates
	CARLIM	Annual carbon limits

III. MACRO CONSTRAINTS

Within each region, there is a single equation to define the maximand UTILITY, and there is a single terminal period constraint, *TC*. All other equations are time-indexed, and refer to the projection periods $t = 1$ (2000), 2 (2010), ... T (2100). They may be grouped as follows:

Macro constraints:		
	UTIL	Discounted utility, sum over all projection periods
	CC	Allocation of total output capacity among expenditure categories
	NEWCAP	New capital stock, excluding energy sector
	TC	Terminal condition on investment and capital stock
	COSTNRG	Cost of energy
Putty-clay constraints:		
	NEWPROD	New vintage production, excluding energy sector
	TOTALPROD	Total production, excluding energy sector
	TOTALCAP	Total capital stock, excluding energy sector
	NEWELEC	New vintage demand for electric energy
	NEWNON	New vintage demand for nonelectric energy
ETA constraints:		
	SUPELEC	Supply of electric energy
	SUPNON	Supply of nonelectric energy
	SUPGAS	Supply of gas
	EXP(EX)	Maximum expansion rate of EX (electric) technologies
	NXP(NX)	Maximum expansion rate of NX (nonelectric) technologies
	DEC(DL)	Maximum decline rate of DL (electric) technologies
	PRVLIM(X)	Production-reserve ratio - exhaustible hydrocarbon resources

RSVAV(X)	Proven reserves available
RSCAV(X)	Undiscovered resources available
RDFLIM(X)	Resource depletion limit
ANC	Annual carbon limit

The *macro* constraints begin with the UTILITY maximand:

$$UTIL: \qquad UTILITY = \sum_{t=1}^{T-1} (udf_t)\,(10)\,(\log C_t) + (udf_T)\,[5 + (udr_T)^{-1}]\,(\log C_T)\,,$$

where the utility discount rate for period $t = udr_t = (kpvs/kgdp) - depr - grow_t$, and the utility discount factor for period $t = udf_t = \prod_{\tau=0}^{t-1} (1 - udr_\tau)^{10}$. These discount rates ensure that the optimal steady-state growth rate will coincide with that assumed for the potential GDP. (The MACRO table contains the $grow_t$ parameters.)

The CC equations indicate that the gross value of production is to be divided between current consumption, investment for building up the stock of capital, and interindustry payments for energy costs:

$$CC_t: \qquad Y_t = C_t + I_t + EC_t \qquad t = 1, \ldots, T$$

The NEWCAP equations describe the dynamics of capital accumulation. Within each 10-year period, net new capital formation is determined by gross investment less depreciation. Since investment is measured as an annual flow, an accumulation factor of 5 is applied to the beginning and ending rate of investment:

$$NEWCAP_{t+1} : KN_{t+1} = 5\,[\,(1\text{-}depr)^{10} I_t + I_{t+1}\,] \qquad t = 0, \ldots, T\text{-}1,$$

where $I_0 = (grow_0 + depr)(kgdp)(gdp_0)$.

At the end of the planning horizon, a terminal constraint is applied to ensure that the rate of investment is adequate to provide for replacement and net growth of the capital stock during the subsequent periods. This reduces "horizon effects", but is not guaranteed to eliminate them entirely. For a more complete discussion of this issue, see SVORONOS (1985).

$$TC_T: \qquad K_T\,(\,grow_T + depr\,) \leq I_T$$

Total interindustry payments for energy costs are determined by the individual cost coefficients ($ecst_i$ and $ncst_{t,j}$) and the activity levels (PE_i and $PN_{j,t}$) for the supply of electric and nonelectric nergy, respectively. There is an additional term included to allow for the fact that oil and natural gas are imperfect economic substitutes. The GN_t activity describes the nonelectric uses of natural gas, and the *ogdp* coefficient reflects the historic oil-gas price differential for this activity. There are quadratic penalty terms associated with the above-normal expansion activities $XPE_{i,t}$ and $XPN_{j,t}$. The penalty coefficients are chosen so that the marginal costs of energy production will be *twice* its long-run normal level if an expansion activity is pushed to its maximum feasible rate during the first decade in which the specific technology becomes available:

$$COSTNRG_t: \quad EC_t = \sum_{i \varepsilon ET} (ecst_i)\,(PE_{i,t}) + \sum_{j \varepsilon NT} (ncst_{t,j})\,(PN_{j,t})$$
$$+ (ogdp)\,(GN_t)$$
$$+ .5\sum_{i \varepsilon EX} \frac{(ecst_i)}{ecapfy_i}\,(XPE_{i,t})^2 + .5\sum_{i \varepsilon NX} \frac{(ncst_{t,j})}{ncapfy_j}\,(XPN_{j,t})^2 \qquad t = 1, \ldots, T$$

To allow for time lags in the response of energy demands to changing prices, there is a putty-clay model of aggregate production. Because energy consumption is closely associated with long-lived capital goods (e.g., residential housing), a sharp distinction is drawn between ex ante and ex post substitutability. That is, there is full substitutability between productive inputs at the time that new vintages of capital stock are generated. The optimal choice of input-mix is determined not only by current but also prospective prices. Once the mix is determined, there are no additional opportunities provided for revision of the input-output coefficients for vintage t. The only flexibility is associated with new capital formation during subsequent time periods.

The output of vintage t is determined by a nested *CES* (constant elasticity of substitution production) function, and depends upon the inputs of capital, labor, electric and non-electric energy. The new vintage production function is of the following form:

$$NEWPROD_t: \qquad YN_t = [\,a(KN_t)^{\rho\alpha}\,(LN_t)^{\rho(1-a)} + b(EN_t)^{\rho\beta}\,(NN_t)^{\rho(1-\beta)}]^{1/\rho} \qquad t = 1, \ldots, T$$

The parameter α (also known as kpvs) may be interpreted as the optimal value share of capital in the value added aggregate term based on a unitary elasticity of substitution between capital and labor. Similarly, the parameter β (also known as *elvs*) may be interpreted as the optimal value share of electricity in the energy aggregate term based upon a unitary elasticity of substitution between electric and nonelectric energy. The parameter ρ is determined by ESUB (the elasticity of substitution between the energy and the value added aggregates) through the following equation: $\rho = 1 - (1/\text{ESUB})$.

A base year benchmarking procedure is employed to determine the coefficients a and b in each region's new vintage production function, NEWPRODt . Let *pnref* denote the "reference" price of nonelectric energy in the base year. (If *pnref* is less than the actual base year price, this procedure will automatically generate some costless conservation in addition to that induced by the *aeei* factor.) Neglecting the time subscripts for this year, a first-order optimality condition then implies that :

$$\partial Y/\partial N = Y^{1-\rho}\, E^{\rho\beta}\, N^{\rho(1-\beta)-1}\, (1-\beta)\, b = pnref$$

Except for b, each element in the preceding equation is known from the base year statistics or from other input parameters. After solving for b, we employ the base year values in the production function NEWPROD. The base year labor force index is defined to be 1.0. This permits us to solve the following equation for the parameter a:

$$Y^{\rho} = a\, K^{\alpha\rho} + b\, E^{\rho\beta}\, N^{\rho(1-\beta)}$$

In order to define the production of output from new vintage capital stocks, it is convenient to assume a geometric decay model of depreciation. If the annual depreciation rate is *depr* and there are ten years between successive time periods, the output from old capital surviving from period t to period t+1 is therefore $Y_t\,(1 - depr)^{10}$. The equation TOTALPROD $_{t+1}$ indicates that total production in period t+1 is the sum of the amounts produced by new investment plus the amounts produced from earlier vintages:

$$TOTALPROD_{t+1}: \quad Y\,N_{t+1} = Y_{t+1} - Y_t\,(1 - depr)^{10} \qquad t = 0. \ldots, T\text{-}1$$

Similarly, the equation TOTALCAP$_{t+1}$ indicates the total capital stock surviving from one period to the next:

$$TOTALCAP_{t+1}: \quad K\,N_{t+1} = K_{t+1} - K_t\,(1 - depr)^{10} \qquad t = 0. \ldots, T\text{-}1$$

The labor force (measured in "efficiency units") is an exogenously specified index number, L_t . Its values are: $L_0 = 1$, and $L_{t+1} = (1+grow_t\,)^{10} L_t$. The labor force available for new vintage production is therefore:

$$L\,N_{t+1} = L_{t+1} - L_t\,(1 - depr)^{10} \qquad t = 0. \ldots, T\text{-}1$$

The new vintage demands for electric and nonelectric energy are:

$$NEWELEC_{t+1}: \quad E\,N_{t+1} = E_{t+1} - E_t\,(1 - depr)^{10} \qquad t = 0. \ldots, T\text{-}1$$

$$NEWNON_{t+1}: \quad N\,N_{t+1} = N_{t+1} - N_t\,(1 - depr)^{10} \qquad t = 0. \ldots, T\text{-}1$$

IV. ETA (ENERGY TECHNOLOGY ASSESSMENT) SUBMODEL

Within the ETA constraints, the first are those labeled SUPELEC. These ensure that the supplies of electric energy will be adequate to cover the demands. In the constraint for period t, the decision variables $PE_{i,t}$ represent the number of kilowatt-hours of electrical energy to be supplied by individual technologies, and the decision variable E_t indicates the number of kilowatt-hours demanded – before allowing for the effects of autonomous energy efficiency improvements. The annual aeei factor (compounded over successive ten-year periods) provides for a costless reduction in the amount of electrical energy to be supplied:

$$SUPELEC_t: \quad \sum_{i \varepsilon ET} P\,E_{i,t} \geq E_t \prod_{\tau=0}^{t-1} (1 - aeei_\tau)^{10}$$

$t = 1, \ldots, T$

In the SUPNON constraints governing the supply-demand balance for nonelectric energy, a similar set of conventions is employed to handle autonomous energy efficiency improvements. Additional terms are needed in order to allow for three decision variables relating to the demand and supply of natural gas: GN (consumption of gas in the form of nonelectric energy), $PN_{gas\text{-}lc}$ (production of low-cost gas) and $PN_{gas\text{-}hc}$ (production of high-cost gas). There is also a term needed in order to allow for the consumption of fuel oil in the electric power sector. This is why the heat rate coefficient ($htrt_{oil\text{-}x}$) is multiplied by the electric energy produced by oil-fired plants ($PE_{oil\text{-}x,t}$).

$$SUPNON_t: \quad \sum_{i \varepsilon NT} P\,N_{i,t} + G\,N - P\,N_{gas\text{-}hc,t} - P\,N_{gas\text{-}hc,t} \geq$$

$$(htrt_{oil\text{-}x})\,(P\,E_{oil\text{-}x,t}) + N_t \prod_{\tau=0}^{t-1} (1 - aeei_\tau)^{10}$$

$t = 0. \ldots, T\text{-}1$

The SUPGAS constraints govern the supply-demand balance for natural gas. Neglecting interregional gas trade, the only quantities available are those supplied by low- and high-cost domestic production. The demands include those for existing gas-fired electricity plants, new gas-fired plants and the amounts of gas employed to supply nonelectric energy demands:

$$SUPGAS_t: \quad P\,N_{gas\text{-}lc,t} + P\,N_{gas\text{-}hc,t} \geq$$

$$(htrt_{gas\text{-}x})\,(P\,E_{gas\text{-}x,t}) + (htrt_{gas\text{-}n})\,(P\,E_{gas\text{-}n,t}) + G\,N_t$$

$t = 0. \ldots, T\text{-}1$

To avoid excessively rapid expansion of new technologies or rapid decline of old ones, there are expansion or decline rate constraints of the following form:

$EXP_{t+1,i}$: $\quad PE_{i,t+1} \leq PE_{i,t}\,(expf)^{10} + XPE_{i,t+1} \quad i \ \varepsilon \ EX$ and $ecap_{t+1,i} > 0$

$NXP_{t+1,j}$: $\quad PN_{i,t+1} \leq PE_{j,t}\,(nxpf)^{10} + XPN_{j,t+1} \quad j \ \varepsilon \ NX$ and $ncap_{t+1,j} > 0.$

$DEC_{t+1,k}$: $\quad PE_{k,t+1} \geq PE_{k,t}\,(decf)^{10} \quad k \ \varepsilon \ DL$

The set X includes four exhaustible hydrocarbon resources: low- and high-cost oil, low- and high-cost gas. Proven reserves are depleted by current production, and are augmented by new discoveries out of the remaining stock of undiscovered resources.

In algebraic terms, these ideas are expressed as follows. For each exhaustible resource belonging to the set X, each period's current production of these resources is determined by a fixed ratio of current production to proven reserves, prv_X :

$PRVLIM_{X,t}$: $\quad PN_{X,t} = prv_X \ RSV_{X,t}$

$$t = 0. \ldots, T$$

Proven reserves available at time t+1 are determined by those at time t plus the time-weighted annual average of gross reserve additions less production (RA_X - PN_X):

$RSVAV_{X,t+1}$: $\quad RSV_{X,t+1} = RSV_{X,t} + 5[(RA_{X,t+1} - PN_{X,t+1}) + (RA_{X,t} - PN_{X,t})]$

$$t = 0. \ldots, T\text{-}1$$

Undiscovered resources remaining available at time t+1 are determined by those at time t *less* the time-weighted average of gross additions to proven reserves:

$RSCAV_{X,t+1}$: $\quad RSC_{X,t} = RSC_{X,t} + 5(RA_{X,t+1} - RA_{X,t})$

$$t = 0. \ldots, T\text{-}1$$

This is almost but not quite a constant ratio model of exhaustible resource depletion. The only element of flexibility lies in the ability to defer reserve additions. Instead of a constant ratio of reserve additions to undiscovered resources, there is an upper limit determined by the resource depletion factor rdf_X :

$RDFLIM_{X,t}$: $\quad RA_{X,t} \leq \ rdf_X \ RSC_{X,t}$

$$t = 0. \ldots, T$$

With this formulation, Global 2100 is able to incorporate the Hotelling feature of forward-looking resource depletion policies. At the same time, the model is capable of representing an important real-world phenomenon. During a given year, a region may be importing oil – and also engaging in domestic production out of both low- and high-cost resources. By contrast, a typical Hotelling model would rule out the possibility of simultaneous production out of different resource cost categories.

The last set of constraints within the ETA submodel are those that refer to the annual carbon emission limits. These are expressed in the form of carbon emission coefficients ($cece_i$ and $cecn_j$ for electric and nonelectric energy respectively) multiplied by activity levels.

$$ANC_t: \quad \sum_{i \varepsilon ET} (cece_i)\,(PE_{i,t}) + \sum_{j \varepsilon NT} (cecn_j)\,(PN_{j,t}) + DC_t - DC_{t-1} \leq nenc + carlim_t$$

$$t = 0. \ldots, T$$

where the parameter $nenc$ is an adjustment to allow for non-energy uses of carbon-based fuels (e.g., lubricating oils and asphalt), and $carlim_t$ is the carbon limit applicable to the specific region. Because of the carbon consumption deferral activities DC_t, the value of carbon cannot rise more rapidly than the marginal productivity of capital.

VI. CONCLUDING COMMENTS - PARALLEL COMPUTATIONS VERSUS AN AGE MODEL

In principle, an AGE framework is more appealing than the "almost consistent" parallel computations methodology adopted here. Several ad hoc simplifications could then be avoided: (1) There would be no need for informal iterations between international oil price scenarios in order to achieve a balance between interregional supplies and demands. There would be no need to solve for the ROW region's oil exports *after* determining the import demands of the OECD region. (2) An AGE model could deal explicitly with international trade in carbon emission rights. It would permit an explicit analysis of the enormous financial transfers that might be involved. (3) An AGE could analyze the impact upon patterns of international trade in carbon-intensive commodities such as iron and steel.

These shortcomings are real, and at some point within the near future it should be possible to remedy them. The difficulties of an AGE approach should not, however, be underestimated. The MPS/GE software (RUTHERFORD [1989]) is probably the best general-purpose tool currently available for the formulation and solution of AGE models. Nonetheless, this package is more difficult to use than GAMS. On today's desk-top computers, MPS/GE is unable to solve problems that are as large as those that can be handled through parallel computations. There is a role for both of these approaches, and there is no reason to allow the best to be the enemy of the good. The "almost consistent" methodology provides useful insights into the economic costs of global CO_2 emission limits, and it serves as an instructive starting-point for the next generation of models in this area.

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SUMMARY

This paper describes Global 2100, an analytical framework for estimating the costs of carbon emission limits. The model is designed to evaluate CO_2-energy-economy interactions. The analysis is based upon parallel computations for five major geopolitical regions: the USA, other OECD nations, the USSR and Eastern Europe, China and ROW (rest of world).

The name Global 2100 has been adopted in order to emphasize both the global nature of the carbon emissions problem and also the need for a long-term perspective. For each region, a dynamic nonlinear optimization is employed to simulate either a market or a planned economy. Supplies and demands are equilibrated within each individual time period, but there are "look-ahead" features to allow for interactions between periods. These interactions are particularly important for the depletion of exhaustible resources and for the accumulation of capital over time.