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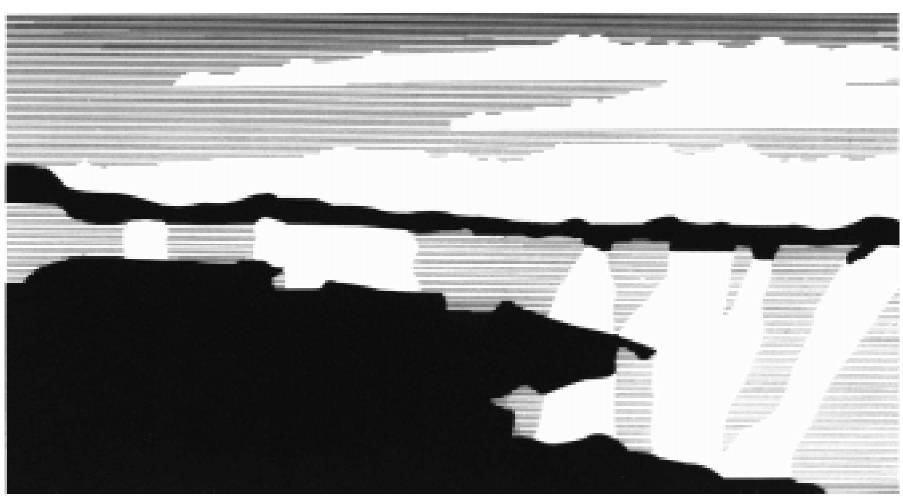

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THE ROLE OF NUCLEAR ENERGY IN MITIGATING GREENHOUSE WARMING

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ABSTRACT

A behavioral, top-down, forced-equilibrium market model of long-term (~2100) global energy-economics interactions* has been modified with a "bottom-up" nuclear energy model and used to construct consistent scenarios describing future impacts of civil nuclear materials flows in an expanding, multi-regional (13) world economy. The relative measures and trade offs between economic (GNP, tax impacts, productivity, *etc*.), environmental (greenhouse gas accumulations, waste accumulation, proliferation risk), and energy (resources, energy mixes, supply-side *versus* demand-side attributes) interactions that emerge from these analyses are focused herein on advancing understanding of the role that nuclear energy (and other non-carbon energy sources) can play in mitigating greenhouse warming. Two ostensibly opposing scenario drivers are investigated: a) demand-side improvements in (non-price-induced) autonomous energy efficiency improvements; and b) supply-side carbon-tax inducements to shift energy mixes towards reduce- or non-carbon forms. In terms of stemming greenhouse warming for minimal cost of greenhouse-gas abatement, a symbiotic combination of these two approaches may offer advantages not found if each is applied separately.

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* For the opportunity to use a recent version of the ERB (Edmonds, Reilly, Barns) global E^3 (energy, economics, environmental) model, J. Edmonds and M. Wise of Battelle Pacific Northwest Laboratory (Washington, DC) are gratefully acknowledged; the use and misuse of the ERB model reported herein, particularly with respect to the modifications made therein, are solely the responsibility of the author.

CONTENTS

I. INTRODUCTION

The Los Alamos Nuclear Vision Project[1,2] is investigating a range of possible futures for nuclear energy using the construct of scenario building[3,4] and an established, relatively transparent global energy model.[5] Both nuclear energy demand and the flow of nuclear materials are examined over a ~100-yr time horizon that is characterized by a range of scenario descriptors or attributes [*e.g.*, population growth, work-force productivity (GDP), autonomous energy efficiency improvements (AEEI, or non-price improvements in transforming primary and secondary energy to energy services), energy resource constraints, carbon taxation schedules, capital- and operating-cost constraints imposed on a range of nuclear energy technologies, *etc*.]. While the focus of past analytical support of the Nuclear Vision Project[6-10] (this string of references describes the evolution of work in progress) has been on issues and concerns related to global implementation of an expanding nuclear fuel cycle, the "top-down" behavioral model of an equilibrium (supply = demand) energy market embodied in the ERB (Edmonds, Reilly, Barns)[5] model adopted and modified for this study also delivers estimates of greenhouse-gas (GHG) emissions. Hence, coupled with the "bottom-up" nuclear energy model[6,7] that has been matched to the recursive, top-down formalism of the ERB model, with this nuclear model providing regional and temporal tracking of plutonium inventories and forms and a relative measures of nuclear proliferation risk[10] based on earlier work,[11-14] top-level energy/economic/environmental (E^3) trade offs become possible.[7,9] Furthermore, by implementing (into ERB) integral-response functions[15] that have been calibrated against a global atmospheric-ocean climate-change model,[16] the GHG emission rates reported by ERB for an array of scenario attributes can be expressed in terms of atmospheric CO_2 accumulations, W(GtonneC), and increases in average global temperature, ΔT(K). Within the limitations of the modified ERB model, and with little additional effort, the role of nuclear energy in mitigating greenhouse warming can be examined under the above-mentioned scenario construct, with all three of the Es in E^3 being touched at some level.

Nuclear energy, like solar and (equilibrated) biomass energies, is a non-carbon (NC) energy source that has clear GHG-mitigating potential. The role played by non-nuclear NC energy sources is limited to the economic constraints that form the basis of the original ERB model,[5] although recent studies of the GHG-mitigating potential of (equilibrated) biomass energy sources has been reported.[17] The present study focuses on the nuclear-energy option, and efforts to consider other NC energy sources in the context of the present effort remains as future work. This present focus on a bottom-up nuclear model without comparable examinations of other NC options is a serious limitation. Furthermore, only electricity generation is considered for the nuclear options being considered; since $\gtrsim$ 60% of all primary energy is applied to fossil-based non-electric applications, this too is a serious limitation of the present study. Lastly, mitigation of greenhouse warming through the implementation of NC energy sources attacks the problem only from the supply side. Increased demand-side energy efficiencies represent the other main facet of the problem.[17-20] This (demand-side) approach to GHC mitigation is examined herein through the aforementioned AEEI parameter; in the context of the ERB model, AEEI is changed parametrically (exogenously). More elaborate (long-term) models reflect endogenous increases in either AEEI,[21] if that concept is used, or induced reallocations of resources among key sectors of the world economies as non-energy sectors adjust to increased energy prices.[22] The ERB model is capable only of exogenous changes in the AEEI-like parameter, ε_k. A fourth limitation of this analysis centers on the merits of economy-based "top-down" models *versus* technology-base "bottom-up" models,[23] the former generally reflects market penalties associated with GHG mitigation schemes, whereas the latter solution-oriented (and generally market-free) approach suggests cost benefits for changing to reduced- or non-carbon fuels and using those fuels more efficiently.

With these four limitations in mind (*i.e.*, nuclear-energy-focus; application only to electricity generation; exogenous AEEI; "top-down" approach), the results summarized in Refs. 8 and 24, along with the associated technical support document,[9] are directed at understanding better the role nuclear energy can play in abating greenhouse warming. After a synoptic narrative describing the ERB model in Sec. II., results are given in Sec. III., which is organized into the following four subsections: a) description of the Basis Scenario; b) impacts on global warming by exogenously varying AEEI (*e.g.*, demand-side impacts); c) the impacts of increased nuclear-energy share fractions induced by imposing a range of carbon-tax schedules (*e.g.*, supply-side impacts); and d) the composite impact on global warming of simultaneous demand-side (increases in AEEI) and supply-side (imposition of carbon taxes) forces. On the basis of these parametric results, a nuclear-energy scenario that mitigates greenhouse warming is suggested in Sec. IV. This "strawman" scenario combines both supply-side (carbon-tax induced increase in nuclear-energy demand) and demand-side (AEEI increases) approaches. Section V. gives interim summary and conclusions, and Appendix A elaborates on the "strawman" scenario.

II. MODEL

Four basic approaches to modeling energy planning have evolved[25] over the years: a) simulations of the technical system *per se*;[26] b) econometric estimates of price-demand relationships;[27] c) sectoral descriptions of whole economies with energy being one of a number of interconnected sectors;[22,28] d) optimization models that combine elements of the others into a Linear Programming (LP) or a Mixed Integer Programming (MIP) formulation.[21,29,30] The ERB model[5] uses a recursive approach to describe a behavioral market equilibrium that internally balances energy production and usage. As such, the simplified ERB formulation models energy from within using econometric price-demand relationships. While simplified compared to the sectoral and/or LP optimizing models, the ERB model targets adequately the (early) needs of the present study, is available to the public, is adaptable to modification, and is generally transparent and well documented.[5] While presenting a “top-down” economist's (market) view of E^3 interactions, an approximate bottom-up technology view of nuclear energy has been added.[6]

The ERB model is comprised of four main parts: supply, demand, energy balance and GHG emissions (a postprocessor). Appropriate carbon coefficients (Gtonne/EJ) are applied at points in the energy flow where carbon is released to the atmosphere; carbon flows where oxidation does not occur are also taken into account. Supply and demand are determined for six primary energy categories: oil(conventional and nonconventional); gas(conventional and nonconventional); solids (coal and biomass); resource-constrained renewables (hydroelectric and geothermal); nuclear (fission, with fusion being included as a form of solar energy[5,31]); and solar (excluding biomass; includes solar electric, wind, tidal, ocean thermal, fusion, and advance renewable; solar thermal is included as a form of energy conservation). The energy balance in ERB assures that supply equals demand in each global regions, with primarily electrical energy is assumed not to be traded (*e.g.*, assumed to be generated and used within a given global region).

Figure 1 gives the structure of the ERB model, as modified for the purposes of the present study. The energy and economic (market-clearing) balances indicated on Fig. 1 are performed for 13 global regions depicted schematically on Fig. 2 and listed in Table I (increased from the nine used in the original ERB model[5]) and for nine times separated by 15-year intervals that start in the base year 1975 and moves out to 2095. Energy balance across regions is established by a set of rules[5] for choosing the respective prices that are required for supply to equal demand in each energy-service group for each fuel. The specific test of convergence requires that the difference in regional sums of demand and supply for each of the three fossil primary fuels (oil, gas, and solids) be less than a specified value.

The demand for energy is determined separately for each of the above-mentioned six primary fuels, for each of 13 global regions, and for each of nine times. Five exogenous inputs (including taxes and tariffs) determine the local energy demand. The base (exogenous) GNP (labor-force productivity $\times$ population) is used as an indicator of both (regional) economic activity and as an index of regional income. The base GNP is modified through price elasticities to model energy-economy interactions, with GNP $\propto$ price for energy-rich regions and GNP $\propto$ 1/price for global regions that must import energy. More specifically, the demand for energy services (*e.g.*, residential/commercial, industrial, and transportation) for each of thirteen (Fig. 2) global regions is determined in ERB by: a) the cost of providing these services; b) the level of income (~GNP); and c) the regional population. Energy services are fueled by an array of four secondary fuels (liquids, gases, solids, and electricity). The mix of these secondary fuels used to provide a given energy service is determined by a cost-based market-share algorithm,[5] as is the demand for fuels used to produce electricity and the share of oil and gas transformed from coal and biomass. The four secondary energy sources are generated from the six primary fuels, with nuclear, hydroelectric, and solar providing only electrical secondary energy; non-electric solar is treated in ERB as a conservation technology to reduce the demand for the three marketed fuels (*e.g.*, oil, gas, and solids). Modeling of the PE $\rightarrow$ SE $\rightarrow$ ES transformation uses a Leontief-type formulation.[32] As is elaborated in Ref. 6, the nuclear energy module added to ERB, for purposes of the present study, replaces the Leontief equation for nuclear, which originally[5] was based only on a scaled cost of uranium extraction (treated in ERB in this regard like a fossil fuel), with one based on capital, operating and maintenance (O&M), and decontamination and decommissioning (D&D) costs. The resulting nuclear energy cost is then fed back to the ERB demand module to determine the respective market-share fraction as a function of time and region. As noted above, this modification lends a “bottom-up” character to the nuclear energy part of the ERB computation. The uranium resource model originally used in ERB,[5] for purposes of the present study, has been replaced with that suggested in Ref. 33, as interpreted in Ref. 34.

Non-price induced improvements in end-use energy efficiency are expressed as a time-dependent index of energy productivity that is independent of energy prices and real income. This parameter is similar to the Autonomous Energy Efficiency Improvement (AEEI) used in other more elaborate (inter-temporal) "top-down" models.[21] This approach allows scenarios to be examined that span the range from continued improvement to technological stagnation, irrespective of world energy prices and real income; the limitations of this approach are discussed in Refs. 23 and 35. World energy prices for all fossil fuels are established through energy balance, with regional (fossil) fuel prices being determined by local taxes, tariffs, and transport charges. Interregional trade, however, does not occur for solar, nuclear, or hydroelectric power. In modeling the GHG-mitigating potential of nuclear energy, the AEEI-like parameter ε_k is varied to express the impacts of demand-side solutions, and carbon taxes are applied as a means to allow NC energy sources to assume a larger market share and to reflect supply-side approaches to abating global warming.

III. RESULTS

Nine of the key scenario attributes varied in the Ref.-9 study are summarize on Table II, along with respective ranges of variations. That study adopted a point-of-departure "Basis Scenario" to which these attribute variations were referenced. The nuclear-energy part of that Basis Scenario was based on once-through LWR operation, a uranium resource and cost scaling described by a Known Resource (KR) category,[33] and a breeder reactor capital cost that is 50% more than that for LWRs. Without a strong carbon tax to stimulate increased demand for nuclear energy (as well as other reduced- or non-carbon energy sources), these conditions were sufficient to push the economic introduction of breeder reactors to beyond the time frame of this computation (2100).[8,9,24] For the purposes of the present investigation of the role that nuclear energy might play in reducing the emission of GHGs, the Ref.-9 Basis Scenario with plutonium (mixed plutonium-uranium oxide, MOX) recycle in LWRs is adopted as the Basis Scenario. As for the Ref.-9 study, other (non-nuclear) attributes remain as given in the original version of the ERB model.

Almost by definition, an "investigation of the role nuclear energy might play in reducing the emission of GHGs" must adopt a supply-side approach. As was shown in Ref. 9, however, simply reducing the cost of nuclear energy (over reasonable limits) to increase market share has a minor impact on GHG emissions. Implementation of a carbon tax that grows at some rate ($/tonneC/yr) has the compounding effects of reducing the use of carbon-based primary energy, increasing the use of NC energy sources (particularly nuclear), and decreasing GWP because of increases in overall energy prices. In this study, implementation of carbon taxes is adopted as the main market force for increasing NC energy supplies while mitigating GHG emission. On the demand side of the equation, increased AEEI is used as a means to examine the relative effectiveness of non-price drivers in reducing GHG emissions. These two supply-side *versus* demand-side approaches to reducing greenhouse warming are then compared. From this comparison, a “nuclear energy scenario” for reduced greenhouse warming is suggested. (Sec. IV. and Appendix A)

A. Basis Scenario

The Basis Scenario adopted for this study is largely that used in Ref. 9, but with plutonium recycle in f^f_{MOX} = 0.3 of the LWR reactor core volume. Figures 3-12 describe the essential elements of this MOX/LWR Basis Scenario. The population and GWP drivers behind this scenario are given in Fig. 3, which also includes *per-capita* GWP, *per-capita* primary energy (PE) demand, and the evolution of the global energy intensity, EI(MJ/$) = PE/GWP. Population growth is exogenously input from U.N. projections, whereas the exogenous base GWP input is modified to reflect changes in the prices of fossil fuels. The dependence of EI results from endogenous shifts in PE and (to a lesser extent) GWP. The evolving mix of primary energy demand for the basis scenario is given on Fig. 4; the diminishing market shares for oil and gas, and the increasing market share for solids (mainly coal, and some biomass) reflect the resource structure used in the ERB model.[5,17] A somewhat disaggregated view of primary- and nuclear-energy demand is depicted in Figs. 5 and 6, respectively. In terms of primary energy, the developing regions become comparable users to OECD countries by ~2025, with a similar condition being reached for nuclear energy by 2050. The strong growth in primary- and nuclear-energy growth for the developing countries after ~2050 is driven largely by the $CHINA^+$ region, as is explicitly shown for nuclear energy in Fig. 6B.

The consequences of this strong growth in nuclear energy for global plutonium inventories is shown in Fig. 7, which also gives total plutonium inventories for the case of no MOX recycle. In these computations, all 13 regions assume the same level of MOX recycle. Some regions ultimately operate with a plutonium “deficit” in order to meet the exogenously determined growth in f_{MOX} and approach to the asymptotic value f^f_{MOX}. In the present version of the model, this deficit is assumed to be met by regions with a plutonium surplus; the difference between “gross” and “net” total plutonium inventories depicted on Fig. 7 reflects these supply-demand requirements. Generally, MOX recycle reduces global plutonium relative to the OT/LWR Basis Scenario of Ref.-9 by a factor of 2-3. This reduction, along with the primary- and nuclear-energy demands shown on Figs. 5 and 6 are in agreement with recent IAEA studies,[36] which in turn derive from a recent IIASA/WEC study.[37]

The global evolution of plutonium inventories by form is shown in Fig. 8, where: ACC = accumulated spent-fuel plutonium that remains efficiently recyclable in LWRs; REC = fully recycled (N = 4 in these computations) and usable only in a fast (neutron) spectrum burner (FSB); SEP = separated plutonium in fuel fabrication (FF) and reprocessing (REP); and REA = plutonium actively undergoing fission in operating LWRs. The plutonium inventories in each of these four forms are used in a multi-attribute utility (MAU) analysis,[10] that has been synthesized from earlier work[11-14] for use in the ERB nuclear model, to yield relative measures of a utility for proliferation, <u>, and a proliferation risk index, PRI. These relative (and highly subjective) measures of proliferation risk are also shown as function of time on Fig. 8. The PRI proliferation metric is adopted as the primary non-economic "cost" for nuclear energy against which any benefit of reduced GHG emission is measured. The integrated carbon-dioxide release, M_{CO_2}(GtonneC), since the beginning of the computation (1975) is also shown on Fig. 8

The rate of CO_2 emission, R_{CO_2}(GtonneC/yr), for this no-carbon-tax Basis Scenario is shown on Fig. 9. The impact of this carbon-dioxide emission rate on integrated emissions, W_o(GtonneC), accumulated atmospheric CO_2 (carbon), W(GtonneC), and average global temperature rise, ΔT(K), is also shown on Fig. 9. The integrated emissions, W_o, is referenced to atmospheric CO_2 inventories since the dawn of the industrial revolution, which is taken as[15] t_{IRV} = 1800, when the atmospheric CO_2 inventory was W_{IRV} = 594 GtonneC. The relatively slow increase of the ratio $\Delta T/(W/W_{IRV})$, as determined from the linear integral-response model used,[15] is also included on Fig. 9. Carbon dioxide emissions from each of the 13 regions tracked by the ERB model is shown in Fig. 10; the $CHINA^+$ region becomes the dominant contributor of GHGs by the year 2025 for this Basis Scenario.

Figure 11 correlates the buildup of global plutonium inventories (Fig. 7) with the relative CO_2 (carbon) accumulation, W/W_{IRV}, or the average global temperature rise, ΔT(K), that results. The latter is computed from the year t_{IRV}. The correlations depicted on Fig. 11 are central to subsequent correlations of global climate change (GCC), nuclear-proliferation, and economic impacts. The Fig.-11 graphs describe an "operating curve" that reflects increased inventories of nuclear materials (if nuclear energy is to play any role in providing energy and mitigating GHC emissions) and increased atmospheric carbon inventories that inevitably accompany a world population that is expanding both in numbers and in *per-capita* energy use.

The risks associated with increased global inventories of plutonium and GHGs are expressed in terms of the PRI and ΔT parameters and are correlated in a reduced "operating curve" for the Basis Scenario on Fig. 12. As important as is the need to translate both PRI and ΔT into economic and social consequences, the present study does not advance beyond the correlation shown given in Fig. 12. This "operating curve" *per se* is not as important to understanding proliferation-risk/GCC/GWP connectivities as are relative shifts in the slopes and magnitudes at a given time as key scenario drivers (*e.g.*, carbon tax rates or exogenously driven AEEI trajectories) are changed. Figure 12 also compares the PRI impacts (for the no-carbon-tax case) of plutonium recycle (f^{f}_{MOX} = 0.30) and the use of the once-through (LWR) fuel cycle. Plutonium recycle increases the PRI by ~10% while have little impact on reducing GCC impacts (*e.g.*, ΔT). Actually the lines of constant time (an isochrone for 2095 is shown on Fig. 12) are almost vertical, with a slight off-vertical orientation indicating that the small added cost associated with the $f^{f}_{MOX} = 0.0 \rightarrow 0.3$ transition, which slightly increases the cost of nuclear energy and reduces (slightly) demand, results in a small increase in fossil-fuel use, and leads to slightly larger values of $\Delta T \lesssim 0.05$ K) for the f^{f}_{MOX} = 0.30 case. Significantly larger impacts are computed for enhanced use of nuclear energy (and other reduced- or non-carbon energy sources) forced by imposing carbon taxes, however. Before results of implementing this supply-side driver are reported (Sec. III.C.), the impact of variations in the demand-side parameter AEEI are first reported.

B. Demand-Side Impacts: AEEI

The parameter ε_{jk}(1/yr) represents a non-price-induced reduction in the amount of secondary energy j (j = liquids, gases, solids, and electricity)[5] needed to provide an energy service k (k = residential/commercial, industrial, and transportation). For the base case, ε_{k} (the j subscript is not used) after the second time period (1990) is 0.0100 1/yr for all regions and all times. As noted in Ref. 35, the parameter AEEI is not well named; as a measure of non-price induced changes in EI, it may neither be autonomous nor deal solely with energy efficiency. The AEEI parameter attempts to account for the impacts of technological developments, (economy) structural changes, and policy-driven inducements in the move towards increased energy efficiency. Many of these forces reflected in AEEI-like effects are endogenous to the economic-energy evolutionary process, and cannot be specified as an external driver. Reference 22, in fact, reported AEEI-like effects from a sectoral model of the economy without explicitly introducing the AEEI parameter.

The scenarios considered under "AEEI variations" examine impacts over the range ε_k = (0.0,0.015), where again ε_k is regionally and temporally (after 1990) constant at the designated value. One case, ε_k = 0.015(RAMP), linearly ramps ε_k from 0.015 (in 1990) to 0.0 in 2095. These impacts are summarized on Figs. 13-18. Specifically, the impact on primary- and nuclear-energy demand is depicted on Figs. 13 and 14, and the (same-basis) fraction of primary energy provided by nuclear energy is shown in Fig. 15. The reflection of these changes in end-used efficiency on the energy intensity (again, starting in 1990) is shown on Fig. 16; ε_k values much below ~0.0050 1/yr, in a globally aggregated sense, freeze any improvement (*e.g.*, decrease) in the global energy intensity, EI(MJ/$).

The range of ε_k values considered not only has a significant impact on primary-energy demand (Fig. 13), but leads to wide swings in carbon-dioxide emissions, as is shown on Fig. 17. The average global temperature rises that result are depicted on Fig. 18. That decreases in ε_k below the 0.0100 1/yr basis-scenario value make an already serious problem more serious comes as no surprise; that 50% increases in ε_k have such relatively weak impact on global warming is. Essentially, across-the-board increases in AEEI result in needed, but insufficient, decreases in GHG emissions; this parameter alone cannot induce changes in the primary-energy mix needed to move aggressively to NC energy sources. The implementation of the supply-side forces embodied in energy taxes based on carbon content can cause such a shift. Unfortunately, if applied regressively, the increased prices that result can drive decreased productivity. These issues are examined, within the limitations of the ERB model, in the following section.

C. Supply-side Impacts: Carbon Taxes

A carbon tax is applied to fossil fuels in proportion to carbon content per unit of released energy. Beginning in 2005, this carbon tax is applied for linearly increasing rates, raning from 0 to 50 $/tonneC/15yr; hence, for a rate of 40 $/tonneC/15yr, the carbon tax at the last time step (2095) would be 240 \$/tonneC. This carbon tax schedule puts the heaviest penalty on coal (23.8 kgC/GJ) and the least penalty on natural gas (13.7 kgC/GJ), with oil being intermediate (19.2 kgC/GJ). According to the ERB algorithms, carbon taxes increase the price of the affected energy source, decrease the market share for that energy source, and reduce the price-based adjustments to the (exogenous) base GNPs. The relationship between energy prices and GNP used in the ERB model derive from the oil shocks of the 1970s, and, as a result, the GNP losses reported by ERB "are unreliable and excessive."[35] In spite of a warning against use of the GNP figures generated by ERB, GNP decrements, ΔGNP, are reported here, along with total cost (tax) figures.

In its present form, collected carbon taxes are not returned to the GNP, but are simply allowed to "disappear". An algorithm was added to ERB to monitor both actual and present-valued carbon taxes and GNP decrements related thereto; these are reported here as a first step towards developing a more sophisticated (*e.g.*, revenue-neutral, import tariffs based on carbon content, *etc.*) carbon tax schedule. For the purposes of the present study, the imposition of carbon taxes is used primarily as a means to increase the price of fossil fuels and to increase the market share of NC energy sources.

The impact of carbon taxes on primary energy use is shown on Fig. 19; at the highest rate of carbon taxation, primary energy use in 2095 could be reduced by ~25% relative to the Basis Scenario. The shift in market shares for the six primary energy sources from the Basis Scenario (no carbon tax) to the case of maximum carbon tax rate (50 \$/tonneC/15yr) is illustrated in Fig. 20; coal looses the greatest market share (~65% $\rightarrow$ 22% in 2095), nuclear and solar (electric) energies show a strong increase in market share (~19% $\rightarrow$ 46% and ~5-6% $\rightarrow$ 13% in 2095, respectively), resource-limited hydroelectric shows only a moderate increase, and gas, while diminishing somewhat in time, shows relatively little change from the Basis Scenario. The shift towards more solar and nuclear energy infers an increase in the use of electricity, which is shown explicitly in Fig. 21; the fraction of primary energy that is used to generate electricity increases from ~16% to 22% in 2095 for the maximum carbon tax rate.

Focusing on nuclear energy, Fig. 22 gives the dependence of annual nuclear energy demand on carbon tax rate. For the 50 \$/tonneC/15yr carbon tax rate, nuclear energy demand increases in 2095 by ~43% relative to the basis scenario. The required deployment rate for this case increases from ~85 GWe/yr to ~75 GWe/yr (for an 80% plant availability factor). Similar deployment rates are required in the out years for the no-carbon-tax case. Figure 23 gives the (same basis) fraction of primary energy demand satisfied by nuclear energy, which in the out years increases from ~18% for the Basis Scenario to ~45% for the strongest carbon tax rate.

Under these circumstances, nuclear energy becomes a major player in the world energy mix. The reduction in atmospheric CO_2 (carbon) emissions that accompanies this carbon-tax-induced increase in nuclear (and solar) energy demand is illustrated in Fig. 24, which also gives *per-capita* and per-primary-energy carbon emission for the Basis Scenario. For the latter, while carbon release per unit of primary energy decreases somewhat, more of this reduced-carbon energy is being used on a *per-capita* basis as prosperity drives a global *per-capita* appetite for energy. The second frame in Fig. 24 elaborates on this impact of carbon taxes on reducing these specific (*per-capita* and per-primary-energy) CO_2 emission rates.

Figure 25 gives a composite curve of fractional reduction of CO_2 emissions ($\Delta R_C/R_C$, relative to the zero-carbon-tax Basis Scenario) as a function of the carbon tax, UC_{TX}($/tonneC), as assembled from the five carbon tax rates being considered. Shown also on this figure is the result of a regression fit to seven econometric, optimization, and hybrid models, as is reported in Ref. 38.

Using the integral-response formulation reported in Ref. 15, and adopting $t_{IRV} = 1800$ as the beginning of the industrial revolution and the beginning of anthroprogenic global warming (W_{IRV} = 594 GtonneC, $\Delta T = 0$), the CO_2 emission rates given on Fig. 24A are used to estimate atmospheric carbon accumulations and related global temperature rises, ΔT(K). These parameters are shown as a function of time for the zero-carbon-tax Basis Scenario and for the highest carbon tax rate (HT, 50 $/tonneC/15yr) on Fig. 26. Figure 27 gives ΔT(K) as a function of time and carbon tax rate. In the out years, the application to a strong carbon tax reduces ΔT(K) from 2.4 K to 1.4 K; these temperature rises are referenced to $t_{IRV} = 1800$ and, based on the model used, has already reached ~0.4 K by the start of this computation (1975).

Whatever “benefits” accrue from the mitigation of global temperature rise (through carbon taxation), these benefits must be compared to “costs” associated with the drivers of this reduced global warming. In the present context, some of these costs are economic [*e.g.*, reduced GNP (note caveats given previously[35]) and an (as yet) unallocated tax stream], some are environmental (*e.g.*, waste streams associated with the increased use of NC energy sources, which are primarily solar and nuclear), and some are social-political (*e.g*., increased risks and altered social structures associated with nuclear proliferation). The following discussions deal first with trade off associated with proliferation risk that accompany increased use of nuclear energy, and then is followed by an illumination if some aspects of adverse economic impacts of imposing unallocated carbon taxes.

At the level of this analysis, the culmination of the comparative risk assessment is the PRI *versus* ΔT relationship (Fig. 12) for this special set of carbon-tax-driven (supply-side) scenarios. In the context of the present study, the evolution of the PRI *versus* ΔT "operating curves" depicted on Fig. 28 represents the final result. As discussed above, with or without a GHC-abating carbon tax, both PRI and ΔT will increase with time as populations in number and living standard develop. The first frame of Fig. 28 gives this PRI *versus* ΔT evolution with increasing carbon tax rates, whereas the second frame stresses more the increased nuclear-energy share under imposition of carbon taxation by giving the fractional increase in PRI relative to the zero-tax case as a function of ΔT. The added sensitivity of plotting $\Delta PRI/PRI_o$ reveals that, for a given taxation rate ($/tonneC/15yr), the fractional increase in PRI shows a maximum at ~2065 that is independent of the rate at which the carbon tax is applied. Generally, increased use of nuclear energy through the imposition of a carbon tax slows the rate of global warming while increasing proliferation risk a few percent relative to the zero-carbon-tax Basis Scenario.

Resolution of the economic costs of this particular set of drivers, as monitored through GNP impacts and unallocated carbon taxes, remains as future work that must ultimately relate abatement costs to achieve a given reduction in ΔT to damage costs associated with accommodation to GCC impacts; these costs are generally expressed as percentages of GNP.[39,40] For present purposes, a unit cost of CO_2 abatement, UC_A($/tonneC), is define as the ratio of reduced CO_2 emissions relative to the Basis Scenario, $\Delta R_{CO_2} = R_{CO_2}(\text{No C-TAX}) - R_{CO_2}(\text{C-TAX})$, to either the total carbon taxes collected for that year, TAX, or the sum TAX + ΔGWP, where ΔGWP = GWP(No C-TAX) – GWP(C-TAX). Figure 29 gives the time dependence of ΔT, TAX, ΔGWP, and these two ways of calculating UC_A. Also shown is the ratio TAX/ΔGWP varying from 2.4 in 2020 to 0.6 in 2095. Attempts to correlate both measures of abatement unit cost with the unit carbon tax, UX_{TX}, are reported on Fig. 30 for the range of carbon tax rates being considered. Based on

$UC_{A,TAX} = TAX/\Delta R_{CO_2}$, high tax rates favor lower "abatement costs" by a factor of ~2. On the other hand, for $UC_{A,TAX + \Delta GWP} = (TAX + \Delta GWP)/\Delta R_{CO_2}$, higher carbon taxes result in ~15% higher "abatement costs". If a "revenue-neutral" carbon tax scheme could be devised and implemented, then TAX + ΔGWP could be reduced in magnitude (and possibly sign).

Some would argue that both TAX(t) and ΔGWP(t) should be discounted at a rate DR(1/yr) to a reference year, summed over the computational period, and expressed in present-value form. Figure 31 gives the decrease in world GNP as a function of the rate of carbon taxation. These GWP percentage decreases are expressed in two forms: a) the percent decrease in the last-year (2095) GWP with and without a carbon tax imposed at a given rate; and b) the percent decrease in the present worth of all GWPs over the study period, using a constant pure discount rate of DR = 0.04 1/yr; the former gives $(\Delta GWP/GWP)_{2095}$ = 4%, and the latter gives $(\Delta GWP/GWP)_{PV}$ = ~0.7%. The ratio of the present value of incremental GWP to the present value of all carbon taxes collected over the computation period, again using DR = 0.04 1/yr, is nominally constant in the range 0.6-0.7; the present value of all carbon taxes collected over the computation period is about twice the present value of the GWP decrement. Again, the previously stated caution about using price-adjusted GNP values from ERB should be kept in mind. Also shown on Fig. 31A is the decrease in atmospheric CO_2 accumulation (again, W_{IRV} = 594 Gtonne is the atmospheric carbon inventory for t_{IRV} = 1800). This reduction in global warming might be considered a benefit against which the decreased GWP could balance, albeit, a more careful and consistent accounting of the collected carbon taxes, as well as a weaker price-GNP scaling,[35] could reduce or reverse the GWP decrements computed from the present model.

The percentage increase in proliferation risk evaluated in the last year, $(\Delta PRI/PRI)_{2095}$, associated with the increased implementation of nuclear energy is also shown on Fig. 31A. While ΔPRI is small relative to PRI, no quantitative statement can be made with respect to this increased proliferation risk attendant to increased use of nuclear energy to abatement GHG accumulation until the consequences of PRI without carbon taxes are fully assessed. Lastly, the second frame in Fig. 31 eliminates the carbon tax rate and plots directly the "benefits" (*e.g.*, reduce ΔT or reduced W/W_{IRV}) against the "costs" (*e.g.*, decreased GWP and increased PRI). This (relative) "benefit-to-cost" assessment, however, remains heuristic until these PRI, GWP, and temperature increments can be related to quantitative social and economic consequences.

D. Composite Demand-Side/Supply-Side Impacts

The relative impacts on stemming greenhouse warming through demand-side (increased AEEI, ε_k = 0.0100 $\rightarrow$ 0.0150 1/yr), supply-side (carbon tax rates, 0 $\rightarrow$ 50 \$/tonneC/15yr), and a combination of both are given a cursory examination in this section. Along with the Basis Scenario (ε_k = 0.0100 1/yr, no carbon tax), the four cases listed in Table III are compared. Figures 32 and 33 give the time dependence of primary-energy and nuclear-energy demand, respectively, for these four case. The nuclear-energy fractions and the energy intensities are displayed on Figs. 34 and 35, respectively. Figure 36 gives the rates of CO_2 emission for these four cases, and the relationship between unit carbon tax, UC_{TX}(\$/tonneC), and the relative (to the basis scenario) decrease in CO_2 emissions is given in Fig. 37. It is noted from Fig. 37 that for a given unit carbon tax, the 25% increase in ε_k results in ~10% additional decrease in the relative CO_2 emission rate. The average global temperature rise for all four cases are summarized on Fig. 38. The bulk of the ~45% decrease in ΔT comes from the supply-side carbon tax, with AEEI contributions being relatively minor. The impact of AEEI on the approximate measures of abatement cost, UC_A(\$/tonneC, Fig. 30), however, can amount to ~33% reductions for the case of UC_A based only on TAX, as is illustrated in Fig 39. For the case of UC_A based on TAX + ΔGWP, the cost reduction for superposing the demand-side abatement solution onto the supply-side solution amounts to ~23%. Hence, while the latter has only a minor impact on reducing ΔT *per se*, a strong economic symbiosis in combining the two may exist. Lastly, a direct comparison of increased proliferation risk (PRI) that accompanies the decreased GCC risk (ΔT) is given in Fig. 40; the combined C-TAX + AEEI attack on global warming reduces somewhat PRI relative to a purely supply-side (carbon tax) strategy, while giving an added (slight) reduction in global warming. A central question, however, is the abatement cost associated with demand-side approaches to reducing GHG emissions.[18,40]

When expressed in normalized form, the impacts of both the demand-side and the supply-side drivers in decreasing globally averaged temperature rise and increasing (C-TAX increases) or decreasing (AEEI increases) nuclear-energy demand are shown on Figs. 41 and 42. Both the Basis Scenario and the combined carbon-tax/AEEI scenario are shown. Lastly, by combining the end points on Figs. 22 and 27, the explicit dependence in ΔT on the demand for nuclear energy in 2095 given in Fig. 43 results; the increase in PRI relative to the Basis Scenario is also included on the last frame of this figure.

IV. SYNTHESES: Scenarios for Stemming Greenhouse Warming

The combination of AEEI (ε_k = 0.0125 1/yr) and carbon-tax (40 \$/tonneC/15yr) scenarios attributes described in Figs. 32-43 is adopted here as a "strawman" scenario for stemming greenhouse warming. This basecase scenario provides essential input to the database schema being developed for the 1997 Intergovernmental Panel on Climate Control (IPCC) Emissions Scenario Project.[46] The IPCC database schema is being built around commercial software.[47] Before formally entering this or other emissions scenarios into this commercial software package, the basecase scenario is first translated from the Fig. 32-43 graphical (and parametric) format into a form that approximates the requirements of the commercial software package, as described in Ref. 46. Appendix A presents this basecase scenario in a form that follows and elaborates on Ref. 46. Figures 44-51 give graphical presentations of much of the tabular input required of the formal relational database,[47] as listed in Appendix A. Specifically, Fig. 44 gives the main drivers and derived parameters for the basecase scenario. The fossil-fuel resources used in the ERB model[5] are displayed according to grade and unit cost in Fig. 45. Figure 46 gives the world-market-clearing fossil primary energy prices to which the ERB model has iterated to meet the conditions that define the basecase scenario; these primary-energy, world-market prices are shown in Fig. 47 for the range of carbon tax rates considered previously (Figs 19-31), including the (40 \$/tonneC/15yr, ε_k = 0.0125 1/yr) basecase scenario being evaluated according to the IPCC scenario schema in Appendix A. The evolution of primary energy demand that results for the basecase scenario is shown in comparison to the Basis Scenario in Fig. 48. Figure 49 gives the electrical energy fractions (of primary energy) for this basecase scenario. The emission rates of the GHGs followed by the ERB model (CO_2, CH_4, and N_2O) for the basecase scenario are shown in Fig. 50, and the consequences of these emissions (based only on CO_2), in terms of atmospheric accumulations and associated average global temperature rises, are depicted on Fig. 51.

Pertinent parts of Figs. 44-51 are expressed in tabular form (Appendix A) in a first attempt to meet the requirements of the database schema described in Ref. 46 and Appendix A. Although the ERB model generates the required information on a (13) regional basis, only global aggregates are reported in Appendix A. Of equal, if not greater, importance to the specific characteristics of this specific scenario, as distilled in the Appendix-A tables, are the parametric sensitivities and trade offs presented in Figs. 13-51.

V. SUMMARY AND CONCLUSIONS

A range of long-term futures for nuclear energy have been examined in Ref. 9 by building "surprise-free" scenarios using a consistent, but simplified, modeling tool.[5] Defining scenario attributes are placed in a hierarchy that divides determinants of nuclear energy futures into external forces and forces that originate from within nuclear energy *per se*. By varying the former upper-level scenario attributes (*e.g*., population, workforce productivity, energy intensity or end-use transformation efficiency, global taxes, top-level nuclear energy economics), a wide range of nuclear energy demand scenarios can be generated. Although these scenarios represent only possibilities, and are not predictions, they nevertheless provide a quantitative basis and connectivity for examining impacts of the lower-level internal drivers that influence directly the economic and operational character of nuclear power. The OT/LWR Basis Scenario adopted in Ref. 9 as a point-of-departure case was modified to include MOX recycle and provided the Basis Scenario for the present study of the impacts of nuclear energy on greenhouse warming. Carbon taxes where used as a supply-side "forcing function" to increase market share of key NC energy sources (mainly solar and nuclear energies). Top-level economic and proliferation-risk implications of this demand-side approach to reducing GHG emissions were examined. As a representative demand-side driver of GHG abatement, the AEEI-like parameter used to define the no-carbon-tax MOX/LWR Basis Scenario (ε_k = 0.0100 1/yr) was varied. It was found that while (exogenously) increased AEEI has only minor impacts on greenhouse warming *per se* (Table III), when used in conjunction with carbon taxes, important decreases in (the highly approximate) measures of unit abatement costs (UC_A, Fig. 39) result. Similar symbiotic effects may also come into play in attempts to mitigate proliferation risks along with GCC risks (Fig. 40).

A central theme of this study is the relationship between economic (*e.g*., ΔGWP, TAX, UC_A, *etc*.), environmental (*e.g*., GCC, proliferation), and energy (*e.g*., AEEI, PE mixes, EI, *etc*.) elements of the E^3 equation. While the relationships demonstrated quantitatively herein are generally based on relative metrics (PRI, ΔT, UC_A, *etc*.) and are far from being comprehensive, this investigation represents a start. Specifically, using the proliferation risk index (PRI) and the estimate of global warming generated from a linear integral-response model[15] that relates GHG emission rates to global temperature rise, ΔT, a range of carbon-tax-driven scenarios was created to examine tradeoffs between increased PRI that accompanies increased use of nuclear energy, decreased global warming, and reduced GWP caused by increased (fossil) energy prices (Figs. 28 and 29). It was found that while strong carbon taxes rates (40-50 $/tonneC/15yr, beginning in 2005) can return CO_2 emission rates in ~2100 to present levels, the rate of global temperature rise, while significantly diminished, remains positive (~0.5 K/yr, compared to 2.8 K/100yr for the case of no carbon taxes). In the 2100 time frame, GWP would be reduced by 3-4% (~0.8% on an integrated present-value basis using a 4%/yr pure discount rate), primary energy used would be reduced by 20-25%, and nuclear energy would experience a ~80% increase (necessitating a deployment rate of ~80 GWe/yr in the out years around 2100). The ratio of present value of all carbon taxes to present value of lost GWP (again, using a 4%/yr pure discount rate) amounts to ~1.3 over most of the computational period. The PRI is increased by only 5-6% for the maximum nuclear-energy implementation (*e.g.*, strongest carbon tax rate) in ~2100. Specifically, the explicit relationship between these relative measures of (increased) proliferation risk and (decreased) global temperature rise (Fig. 28) indicates that for this 5-6% increase in PRI, ΔT in 2100 is reduced form 2.4 K for the no-carbon-tax case to 1.4-1.5 K, but again, global temperature continues to rise at a rate of 0.5 K/yr in 2100 for the strong carbon tax rates. These correlative results between proliferation risk and GCC impacts, however, project only relative trends; the "real" implications of the base (*e.g.*, for no carbon tax) PRI growing to ~0.14, ± 5-6% with or without carbon-tax-induced growths in nuclear energy, along with the assessment of "actual" impacts of decreasing the global temperature rise by ~ 1 K over ~100 years needs resolution.

Finally, an emissions scenario base case was synthesized from the Basis Scenario by implementing both supply-side (carbon tax rate increased from 0 to 40 $/tonneC/15yr) and demand-side (AEEI-like parameter ε_k increased from 0.0100 1/yr to 0.0125 1/yr) drivers. As in indicated n Fig. 43, this 25% increase in (global) AEEI reduces the amount of nuclear energy required for a ~90% reduction in global warming (in 2095) by ~30%. This symbiotic combination of supply-side and demand-side approaches to stemming greenhouse warming is presented for preliminary consideration by the IPCC New Emissions Scenario Project ,[46] as is reported in Appendix A.

Throughout the narrative leading to the "strawman" scenario described in Appendix A, a number of shortcomings and areas of future work were identified, many of which are related to differences in "top-down" *versus* "bottom-up" modeling approaches.[23,35] These shortcomings and areas of future work are summarized as follows:

- **AEEI Parameter:** The simplified, exogenous variation of the parameter ε_k only crudely approximates complex, endogenous interactions between technology improvements, (economy) structural (sectoral) interactions, and policy-driven behavioral changes;[35] schemes to endogenize AEEI-like parameters should be investigated.
- **GNP Feedback:** As approximate as the price-GNP feedback in ERB is, the calibration of this feedback is based on responses to the oil crises of the 1970s and, hence, may be overly responsive;[35] re-calibration and parametric sensitivity studies need to be performed.
- **Carbon Taxation:** The impact of carbon taxes on GNP, as modeled in ERB, is only though the above-described price-GNP feedback; no attempt has been made in these computations in enforce revenue-neutral (or better) schemes to return these taxes to the regional GNP streams; higher-fidelity taxation and (carbon) rights-trading schemes must be investigated.
- **Regional Variations:** The results presented herein pertain to a generally uniform globe; no attempt was made to tailor rates of carbon taxation, AEEI improvements, or nuclear-energy deployment on a regional basis to optimize all elements of the E^3 equation on a global basis; region-based growth scenarios must be developed.
- **Quantitative Metrics:** While the GNP impacts are quantitative, in spite of the limitations listed above, the GCC metric (ΔT) and the proliferation risk metric (PRI) remain qualitative in terms of real economic welfare impacts; attempts must be made to quantify economic impacts of PRI and ΔT.
- **Non-Carbon Energy Sources:** The focus of this study has been on nuclear energy as a NC energy source, and even then only in so far as electricity generation is concerned; improved modeling of both solar and biomass[17] sources in the context of the present version of the ERB model is needed.
- **Nuclear Energy Model:** While attempts were made to introduce a "bottom-up" flavor into the nuclear model[6] used in the "top-down" ERB model, more remains to be done:[9]

- **Nuclear Costing:** Attempts to fit a "bottom-up" feature in the costing of nuclear energy to the generically "top-down" ERB model need expansion to include more detail in both the fuel cycle and the capital cost inputs to the composite unit cost of energy used in ERB ultimately to determine nuclear energy market shares and related proliferation *versus* climate-change tradeoffs; central to improving fuel-cycle costing algorithms is the need to select regional and temporal plutonium recycle options based on economics rather than (region-dependent) exogenous drivers.
- **Nuclear Materials Flows/Inventories:** While resolution into ACC, REC, SEP = FF + RP, and REA forms with which proliferation risks can be assessed is adequate, a rule-based algorithm for inter-regional transport and accumulations of plutonium based both on costs and sanctions needs to be developed to resolve and optimize local plutonium demand and supply; as noted below, consideration of both commercial Liquid Metal (Breeder) Reactors (LMRs) and LWR-supportive Fast-Spectrum Burners (FSBs) expand the scope of this issue.
- **Breeder Requirements:** Integration of plutonium requirements of an evolving breeder economy *vis á vis* a coupling of regional and temporal breeding ratios to other parts of the nuclear fuel cycle is needed for any study that seriously evaluates and optimizes the potential and need for breeder reactors; the strong introduction of carbon-tax-induced nuclear energy, depending on which uranium-resource "reality" is adopted,[9,33] may advance the date for economic introduction of breeder reactors;
- **Fast Spectrum Burners:** Comments made in connection with the last three items as related to improved understanding of the short- and long-term role of FSBs in closing the nuclear fuel cycle apply here also.
- **Neutronics:** The neutronics model used to feed the nuclear materials flow and inventory model represents a highly approximate description of the time-averaged reactor core isotopics; the relationships between the many parameters listed on Fig. 3B and in Table IV of Ref. 9 need a firmer connection with "real" neutronics computations, particularly with regard to the averaged relationships between beginning- and end-of-life plutonium concentrations, overall fuel burnup, MOX core volume fractions, and fissions occurring in bred material.

- **Fuel Cycle:** The impact of innovative/emerging fuel cycles (high-burnup, partial separations, non-aqueous processing, supportive transmutors, reactor integration, *etc*. on cost and proliferation risk needs detailed technological and economic assessment.

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NOMENCLATURE

ACC	recyclable (to LWRs) accumulated plutonium; also, accelerator
AEEI	Autonomous Energy Efficiency Improvement
AFR (Mha/yr)	aforestation rate
ANI(M)	animal numbers
AWA	animal waste emission source
ATW	Accelerator Transmutation of Waste
BAU	business as usual
BIB	biomass burning emission source
BMT (EJ/yr)	total biomass
CCV (tonneC/ha)	carbon content for vegetation
C-TAX	carbon tax
CAN	Canada
$CHINA^+$	China
CIS	Commonwealth of Independent States (FSU)
COA (EJ/yr)	coal
COE(mill/kWeh)	cost of electricity
CON (EJ/yr)	consumption
CR	conventional uranium resources
D&D	decontamination and decommissioning
DEF	deforestation emission source
DEV	developing countries (ME + NAFR + SAFR + LA + IND + SEA)
DFR (Mha/yr)	deforestation rate
DR(1/yr)	discount rate (for proliferation risk discounting[11,12,38], or for estimating present worths of GWP or carbon taxes)
E(kWeh)	annual electrical generation
E^3	economics/energy/environmental
EEU	Eastern Europe
EGE (EJ/yr)	electricity generation
EI(GJ/$)	energy intensity, ratio of primary or final energy to GNP
EIN	industrial sector EUP emission source
EQV (Mtonne/yr)	CO_2 equivalent
ERB	Edmonds, Reilly, Barns model[5]
ERE	residential EUP emission source
ES	energy services (residential/commercial, transportation, industrial)
ETR	transport EUP emission source
EUP	energy use and production GHG emission source
EXI (EJ/yr)	export/import
FC	nuclear fuel cycle
FER	fertilized soil emission source
FF	fuel fabrication
FP	fission product
FSB	fast spectrum burner (LMR/IFR, ATW)
FSU	Former Soviet Union
f_{MOX}	volume fraction of LWR core that is MOX
f_{MOX}^f	final (asymptotic) volume fraction of LWR core that is MOX
GAG	gain in agriculture emission source
G(B$)	gross world product, also GWP
GCC	global climate change
GDP($)	gross domestic product
GHG	greenhouse gas

GNP($)	gross national product
GWP($)	gross world product
HT	high carbon tax rate (50 $/tonneC/15yr)
HV	high (nuclear energy growth) variant
HYDRO	hydroelectric
HYD (EJ/yr)	hydroelectric
I_j(kgPu)	plutonium inventory (j = ACC, REC, REA, SEP, *etc*.)
IAEA	International Atomic Energy Agency
ID	identification
IFR	Integral Fast Reactor
IIASA	International Institute for Applied Systems Analysis
IND	India
IPCC	Intergovernmental Panel on Climate Change
IRV	industrial revolution
j	ERB index for secondary energy (SE)
k	ERB index for energy services (ES)
LA	Latin America
LFI	landfill emission source
LMR	liquid metal reactor
LV	low (nuclear energy growth) variant
LWR	light water reactor
KR	known uranium resources
l	ERB index for region
M_{CO_2} (Gtonne)	accumulated CO_2 emissions
$\dot{M}_{CO_2}$ (Gtonne/yr)	rate of CO_2 emissions
MAU	multi-attribute utility (analysis)
ME	Middle East
MM	(uranium) mining and milling
MIP	mixed integer programming
MIT	Massachusetts Institute of Technology
MOX	mixed (uranium, plutonium) oxide fuel
MV	medium (nuclear energy growth) variant
m	ERB index for time
N	number of MOX recycles; nonintervention scenario class
NA	not available
NAFR	Northern Africa
NAT	nature emission source
NE	nuclear energy
NGA (EJ/yr)	natural gas
NGP (EJ/yr)	produced natural gas
NM	nuclear materials
NT	no carbon taxes
NUB (EJ/yr)	nuclear breeder electric
NUE (EJ/yr)	non-breeder nuclear electric generators
NUCL	nuclear
NUN (EJ/yr)	nuclear non-electric
nl	number of regions modeled in ERB (nl = 13)
O&M	operation and maintenance
OECD	Organization for Economic Co-operation and Development (USA + CAN + OECD-E + OECD-P)
OECD-E	OECD-Europe
OECD-P	OECD-Pacific

OIL (EJ/yr)	oil
OIP (EJ/yr)	produced oil
OIS (EJ/yr)	synoil
ORNL	Oak Ridge National Laboratory
OT	once-through (LWR)
P	parametric variation scenario class
P_E(MWe)	net electric generation capacity
P_{ET}(MWe)	total electric generation capacity
PE	primary energy [oil, gas, solids (coal + biomass), nuclear solar, hydroelectric]
POP	population
PRI	proliferation risk index
PRI_o	proliferation risk index without carbon taxes
PRO (EJ/yr)	production
PRP	production process emission source
PV	present value computed using discount rate DR
ppmv	volume parts per million
p_f	plant capacity factor
$R_{CO_{2,1}}$(Gtonne/yr)	carbon emission rate from l^{th} region; for world total, (l = nl +1), same as M_{CO_2}
RAC (Mha)	rice acerage
REA	reactor plutonium
REC	fully recycle (N recycles to LWRs) plutonium
REF	(economically) reforming countries (EEU + FSU); also, reference time (1975)
REL (EJ/yr)	renewable electric generation
RFI	rice fields emission source
RNE (EJ/yr)	renewable non-electric
RP	reprocessing
RPU	reactor plutonium
RS	repository
RW	world regions
RYE (tonne/ha)	rice yield
SAFR	Southern Africa
SE	secondary energy (liquids, gases, solids, electricity)
SEW	sewage emission source
SE/PE	PE $\rightarrow$ SE conversion efficiency
SEA	South and East Asia
SEP	separated plutonium
SF	spent fuel
SFT	total spent fuel
SLD (EJ/yr)	solid fuels (coal + biomass)
SLE (EJ/yr)	solar electric
SLT (EJ/yr)	solar non-electric
SPU	separated plutonium (RP + FF)
TAX	carbon tax case designator
TEG (EJ/yr)	total electric generation
TH	thermal $\rightarrow$ electric conversion
TPE (EJ/yr)	total primary energy
TOT	total, world
TOT	total emission source
TR	transportation, total uranium resources

TX	present worth of carbon taxes over period to 2095
t(yr)	time
t_{IRV}	time industrial revolution commences, 1800
t_{REF}	reference time or base year for ERB, 1975
USA	United States of America
UTC_j(\$/We)	unit total cost of j^{th} nuclear energy system
<u>	grand utility function[10]
W(GtonneC)	atmospheric carbon-dioxide (carbon) accumulation
W_o(GtonneC)	integrated atmospheric carbon-dioxide (carbon) emissions, since t_{IRV} = 1800
W_{IRV}(GtonneC)	atmospheric carbon-dioxide (carbon) at time t_{IRV} = 1800 (594 Gtonne, or 289 ppmv, given 2.13 GtonneC/ppmv)[15]
We	electrical Watt
Wt	thermal Watt
WEC	World Energy Council
Z_{lm}	population in region l at time interval m
ΔT(K)	average global temperature rise, referenced to time t_{IRV} = 1800
ε_i(1/yr)	annual growth rate of entity i (i = POP, EI, PE, NE, *etc.*)
ε_k(1/yr)	annual growth rate of SE(j) $\rightarrow$ ES(k) transformation efficiencies
η_{TH}	thermal-electric conversion efficiency

APPENDIX A. Database Schema for the 1997 IPCC Emission Scenario Project[46]

This Appendix follows the database schema reported in Ref. 46 in a preliminary application to the basecase scenario developed in Sec. III.D. The "graphical database" for this basecase, as embodied in Figs. 32-43, is translated into the Ref.-46 schema, which is composed of the following eight tables arrayed in a relational database proved by the commercial software product ACCESS:[47] 1) Source Table; 2) Scenario Table; 3) Source Region Table; 4) Region Definition Table; 5) Assumption Table; 6) Energy Sector Table; 7) Emissions Table; and 8) Consequence Table. In the spirit of a "strawman" approach, information is presented only at a globally aggregated level, even though results from the ERB model are generated for each of 13 regions (Fig. 2). The material presented in this Appendix follows the format that will eventually be required for entry into the commercial relational database[47] for use by the IPCC Emission Scenario Project[46].

1. Source Table (Sou_{Code}): ERB

   1.1. Reference: J. Edmonds and J. M. Reilly, Global Energy: Assessing the Future, Oxford University Press, New York (1985); M. A. Wise, private communication, Battelle Pacific Northwest Laboratory, Washington D.C. (1995).

   1.2. Authors: J. Edmonds, J. M. Reilly, D. W. Barns

   1.3. Update: M. A. Wise, private communication, Battelle Pacific Northwest Laboratory, Washington D.C. (1995).

   1.4. Model Type ($Model_{Type}$): top-down recursive equilibrium with bottom-up nuclear-energy module.

   1.5. Database: update of J. Edmonds and J. M. Reilly, as described in technical support document LA-UR-97-3826 (September 24, 1997)[9] and the main body of this report.

2. Scenario (Sce_{Code}) Table ($Sce_{Code} \rightarrow Sou_{Code}$)

   2.1. Scenario Class (Sce_{Class}): nonintervention (N), parametric variations (P)

2.2. Scenario Description ($Sce_{Description}$): described in technical support documents LA-UR-97-3826 (September 24, 1997)[9] and the main body of this report; underlying story line: Starting in 1975 and marching to 2095 through nine recursively equilibrated world market equilibria, the impacts of demand-side autonomous energy efficiency improvements (AEEI) and supply-side carbon taxes (C-TAX) on stemming global warming is examined parametrically; a symbiotic combination of these demand-side and supply-sided approaches is selected as the basis scenario for this IPCC-1997 submittal.

3. Source Region (Sou_{Reg}) Table: 13RW (13 world regions)

4. Region Definitions ($Region_{Definition}$) Table [% population (5271 M in 1990) / % land area (134×10^6 km^2, excluding antarctica) / persons/km^3 (39.1 persons/km^2 average)]; refer to Fig. 2 in technical support document LA-UR-97-3826 (September 24, 1997)[9], and Fig. 44 in the main body of this report.

4.1. $Region_{USA}$: United States of America (4.72/6.79/27.17)

4.2. $Region_{CAN}$: Canada (0.51/7.40/2.67)

4.3. $Region_{OECD\text{-}E}$: Andorra, Austria, Azores, Belgium, Denmark, Faeroe Islands, Finland, France, Germany, Gibraltar, Greece, Greenland, Guernsey, Iceland, Ireland, Isle of Man, Italy, Jersey, Liechtenstein, Luxembourg, Madeira, Malta, Monaco, Netherlands, Norway, Portugal, Spain, Sweden, Switzerland, Turkey, United Kingdom (8.22/4.94/65.07)

4.4. $Region_{OECD\text{-}P}$: Australia, Japan, New Caledonia, New Zealand, South Korea (3.55/6.26/22.26)

4.5. $Region_{EEU}$: Albania, Slovenia, Bulgaria, Czechoslovakia, Czech Republic, Slovakia, Hungary, Poland, Romania, Yugoslavia, Yugoslavia [Fed. Rep.], Bosnia-Herzegovina, Croatia, Macedonia (2.34/0.87/105.78)

4.6. $Region_{FSU}$: Armenia, Azerbaijan, Belarus, Estonia, Georgia, Kazakhstan, Krygystan, Latvia, Lithuania, Moldova, Russia, Tadzhikistan, Turkmenistan, Ukraine, Uzbekistan (5.50/16.18/13.28)

4.7. $Region_{CHINA^+}$: Cambodia, China, Laos, Mongolia, North Korea, Vietnam (23.80/8.89/101.44)

4.8. $Region_{ME}$: Bahrain, Gaza Strip, Iran, Iraq, Israel, Israeli-held Territories, Jordan, Kuwait, Lebanon, Oman, Qatar, Saudi Arabia, Syria, United Arab Emirates, Yemen (2.51/4.07/24.13)

4.9. $Region_{NAFR}$: Algeria, Chad, Egypt, Libya, Mali, Mauitania, Morocco, Niger, Sudan, Tunisia, Western Sahara (3.12/9.89/9.89)

4.10. $Region_{RAFR}$: Angola, Benin, Botswana, Burkina Faso, Burundi, Cameroon, Cape Verde, Central African Empire, Comoros, Congo, Djibouti, Equitorial Guinea, Eritrea, Ethiopia, Gabon, Gambia, Ghana, Guinea, Guinea Bissau, Ivory Coast, Kenya, Lesotho, Liberia, Madagascar, Malawi, Mauritius, Mayotte, Mozambique, Namibia, Nigeria, Reunion, Rwanda, Sao Tome, Senegal, Seychelles, Siere Leone, Somalia, South Africa, Swaziland, Tanzania, Togo, Uganda, Zaire, Zambia, Zimbabwe (8.07/12.56/25.11)

4.11. $Region_{LA}$: Anguilla, Antigua and Barbuda, Argentine, Aruba, Bahamas, Barbados, Belize, Bermuda, Bolivia, Brazil, Cayman Islands, Chile, Colombia, Costa Rica, Cuba, Dominica, Dominican Republic, Ecuador, El Salvador, Falkland Islands, French Guiana, Grenada, Guadeloupe, Guatamala, Guyana, Haiti, Honduras, Jamaica, Martinique, Mexico, Montserrat, Netherlands Antilles, Nicaragua, Panama, Paraguay, Peru, Puerto Rico, St. Kitts and Nevis, St. Lucia, St. Vincent, Surinam, Trinidad, Turks and Caicos Islands, U.K. Virgin Islands, Uruguay, Venezuela (8.37/15.24/21.47)

4.12. $Region_{IND}$: India (16.05/2.36/265.79)

4.13. $Region_{SEA}$: Afghanistan, Bangladesh, Bhutan, Brunei, Fiji, French Polynesia, Hong Kong, Indonesia, Kiribati, Macau, Malaysia, Maldives, Marshall Islands, Marshall Islands, Micronesia, Myanmar, Nepal, Pakistan, Palau Islands, Papua New Guinea, Philippines, Singapore, Solomon Islands, Sri Lanka, Taiwan, Thailand, Tonga, Vanatu, Western Samoa (12.95/4.56/110.97)

5. Assumption Table: ($Sou_{Code} \rightarrow Sce_{Code} \rightarrow Reg_{Code} \rightarrow$ Year)

5.1. Gross World Product, GWP(B$): refer to Fig. 44 in the main body of this report; these values represent recursively energy-price-adjusted values of a set of basis GNP values; these basis values are used unaltered from the data set originally provide with the ERB model.[48]

year	GWP[a] (T$)
1975	13.15
1990	21.67
2005	32.44
2020	46.68
2035	64.22
2050	86.92
2065	114.25
2080	152.26
2095	204.60

[a] available for each of 13 global regions (re: Item 4.)

5.2 World population, POP(M): refer to Fig. 44 in main body of this report:

year	POB[a] (B)
1975	3.97
1990	5.22
2005	6.46
2020	7.63
2035	8.70
2050	9.64
2065	10.45
2080	11.14
2095	11.70

[a] available for each of 13 global regions (re: Item 4.)

5.3 International Crude Oil Price, COP($/bbl):

5.3.1. Fossil fuel resources: the resources of oil, gas, coal, and unconventional oil are taken directly from the database that accompanies the ERB model. These resources are displayed as a function of (5) grade and as a function of cost (1975 $) in Fig. 45, and are used unaltered in the present analysis.

5.3.2. The world prices for the three primary fossil energy sources (oil, gas, and coal) are determined in ERB through a market-clearing algorithm into which is factored all regional taxes (including carbon taxes) and tariffs, resource costs, and environmentally related extraction costs. The convergence that leads to supply equaling demand is forced at each of the nine times analyzed by ERB. Figure 46 gives these world prices, pim(1975$/GJ), as a function of time (m) and primary fossil energy source i (oil, i = 1; gas, i = 2; and coal, i =3), for the base case being considered (carbon tax rate = 40 $/tonneC/15yr, ε_k = 0.0125 1/yr); Figure 47 gives the time-evolution of pim(1975$/GJ) for the Basis Scenario (zero carbon tax, ε_k = 0.0100 1/yr), and a range of carbon tax rates. The basis of Fig. 46 is listed below (42 GJ/toe $\times$ 0.136 tonne/bbl $\Rightarrow$ 5.712 GJ/bbl).

year	World Fossil Energy Prices (1975$/GJ)		
	oil	gas	coal
1975	1.84	0.63	0.51
1990	2.35	1.03	0.65
2005	4.19	1.30	0.86
2020	5.08	1.45	1.04
2035	5.30	1.44	0.98
2050	5.74	1.50	0.92
2065	7.17	1.53	1.14
2080	7.50	1.53	1.08
2095	7.55	1.56	0.96

5.4. Autonomous Energy Efficiency Improvement, AEEI(1/yr): 0.0100 1/yr for all regions for all times after 1990; parametrically varied over the range (0.0,0.0150). The impact of these variations on energy demand, energy mixes, and carbon-dioxide emissions is shown on Figs. 13-18 of the main body of this report:

5.5. Deforestration Rate, DFR(Mha/yr): NA

5.6. Aforestation Rate, AFR(Mha/yr): NA

5.7. Carbon Content for Vegetation, CCV(tonneC/ha): NA

5.8. Animal Numbers, ANI(M): NA

5.9. Rice Yield, RYE(tonne/ha): NA

5.10. Rice Acreage, RAC(Mha): NA

5.11. Methane emissions from rice fields, tonneCH_4/ha/yr: NA

5.12. Energy Value of ?????, Eng_{Value}(toe/yr): NA

5.13. Carbon content of primary fossil fuels use in ERB[5]:

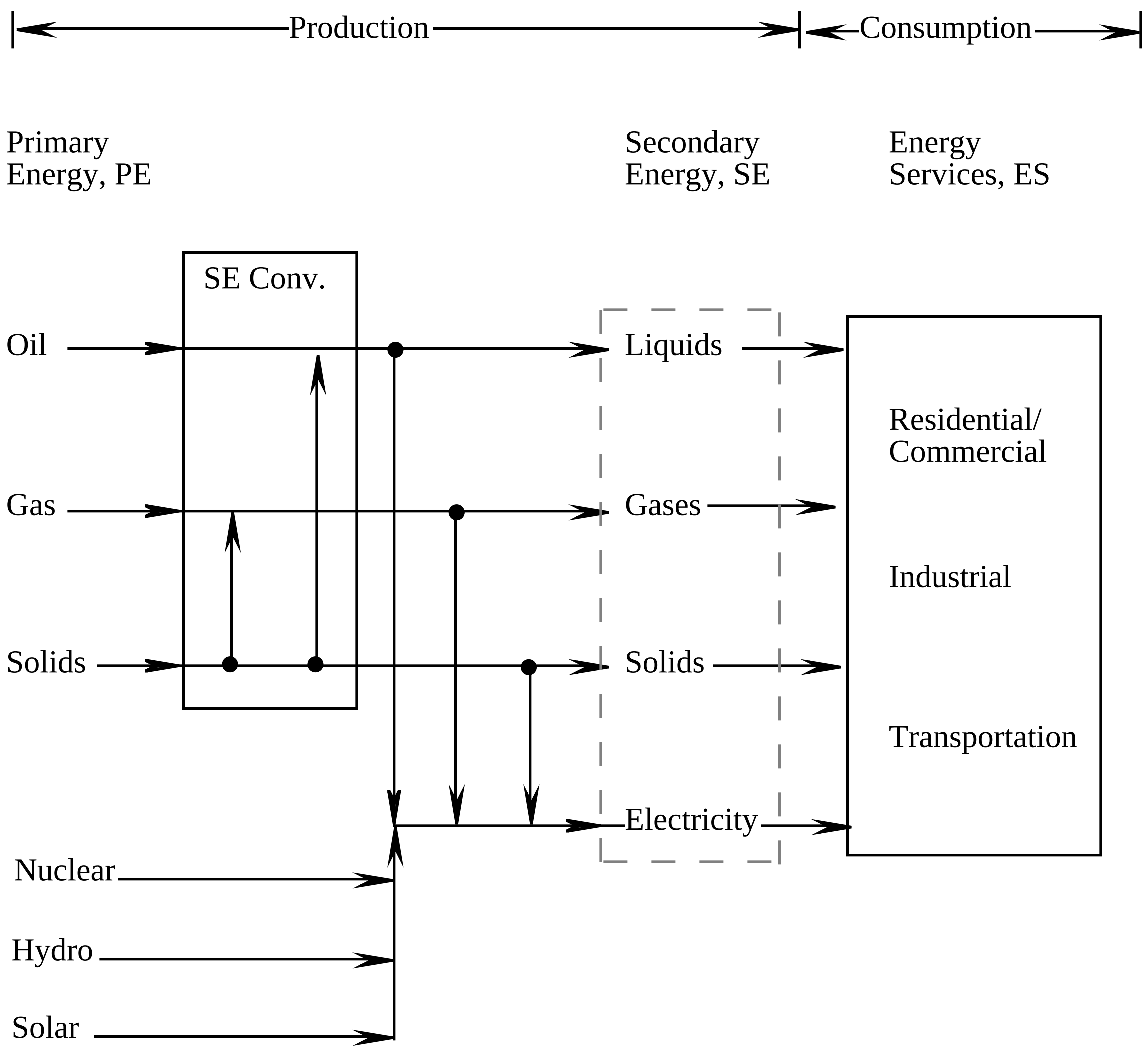
Fuel	Carbon Coefficient (kgC/GJ)
oil	19.2
gas	13.7
coal	23.8
coal gasification	40.7
coal liquification	38.6
shale oil[(a)]	41.8

[(a)] Western U.S. shale oil from carbonate rock.

6. Energy Sector ($Energy_{Sector}$) Table ($Sou_{Code} \rightarrow Sce_{Code} \rightarrow Reg_{Code} \rightarrow$ Year $\rightarrow Eng_{Product} \rightarrow Eng_{Flow} \rightarrow Eng_{Value}$):

The Energy-Product and Energy-Flow schema depicted in the following sections have been modified (expanded) to reflect the (Primary Energy, PE) → (Secondary Energy, SE) → (Energy Service, ES) logic used in the ERB model against which results for the C-TAX/AEEI scenarios considered herein must be presented on both (13) regional and global levels. Only global results are presented in this trail submittal. The Energy-Product/Energy-Flow schema use in ERB is reproduced below: The main differences with respect to the IPCC schema being suggested are: a) the separation of "Consumption" and "Electricity Generation"; and b) the unaccounting of synthetic gas and liquids from solids; and c) a somewhat thinner resolution of both nuclear- and renewable-energy options.

Energy-Product/Energy-Flow Schema Use in the ERB Model[5]



6.1. Energy Product ($Eng_{Product}$) IPCC Schema, Giving Modifications (Expansions) Added Notation:

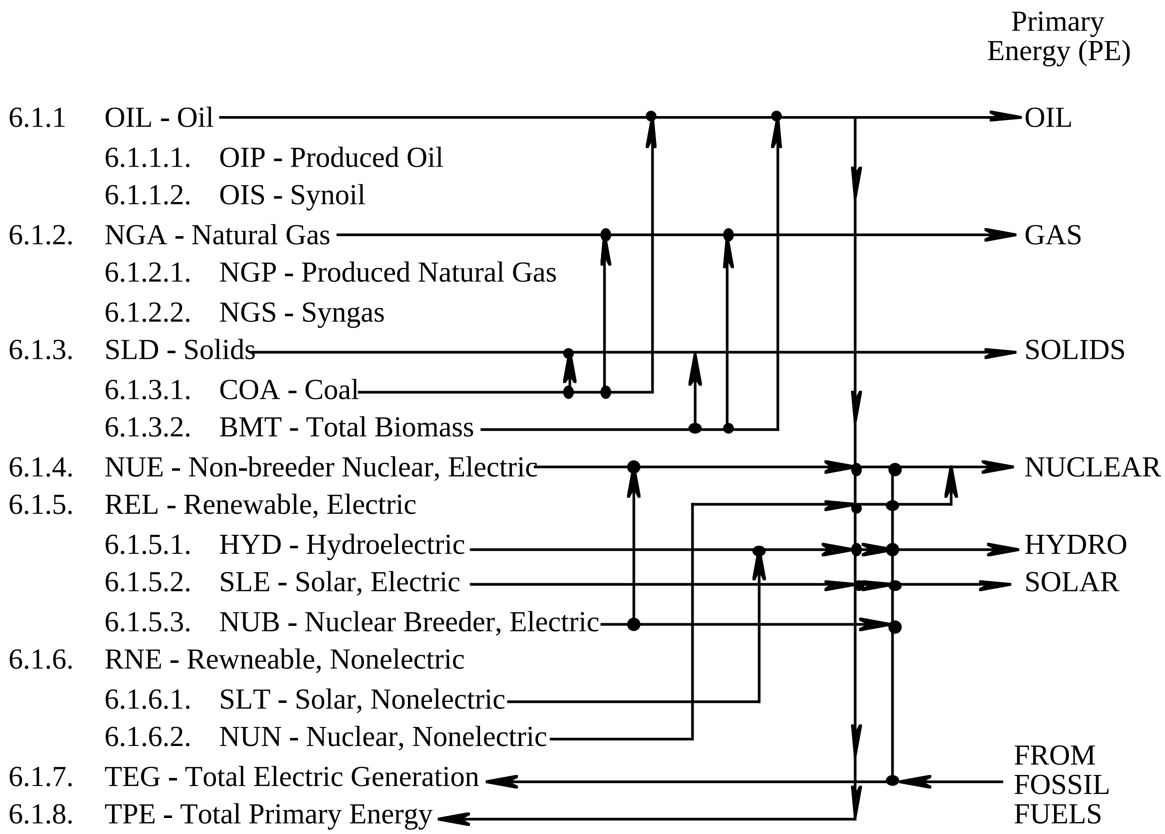


Figure 48A gives the time evolution of the six Primary-Energy sources for the base case being considered (carbon tax rate of 40 \$/tonneC/15yr and and AEEI rate of ε_k = 0.0125 1/yr). Figure 48B gives a similar plot for the Basis Scenario (no carbon tax, ε_k = 0.0100 1/yr). The fraction of PE provided electricity (not same basis) is given in Fig. 49, which, in addition to world-averaged values, gives these fractions for OECD, Reforming Economies (REF = FSU + EEU), and developing (DEV) countries. The essential elments of Figs 48 and 49 are listed below.

World Primary Energy Demand (EJ/yr, Fig. 48A)[a]

year	oil	gas	coal	nuclear[b]	solar[b]	hydro[b]	TPE	electric demand[c]
1975	103.4	69.1	63.9	9.0	---	18.4	263.8	86.2
1990	131.7	63.7	89.2	25.6	---	22.9	333.0	147.0
2005	127.5	87.5	97.7	42.1	---	30.4	385.5	154.2
2020	133.5	104.1	85.6	60.5	7.9	32.7	424.2	198.0
2035	137.7	98.6	84.5	95.5	27.0	51.9	495.3	273.4
2050	71.6	86.2	134.2	197.4	59.3	73.3	621.8	428.2
2080	51.8	80.0	165.2	268.9	79.7	83.1	728.5	531.1
2095	41.5	74.4	194.3	348.3	106.6	91.7	855.8	648.4

(a) available for each of 13 global regions (re: Item 4.)

(b) electricity generation only; ERB treats solar thermal as a form of energy conservation.

(c) thermal basis; global average ratio of electricity supply to demand is 0.28.

6.2 Energy Flow, (Eng_{Flow}):

6.2.1. CON - Consumption

6.2.2. PRO - Production

6.2.3. EXI - Export/Import

6.2.4. EGE - Electricity Generation

6..3. Energy Product-Flow:

Since only global results are presented in this trial submittal, the Export/Import (EXI) part of this matrix in inactive.

Product/Flow	CON	PRO	EXI	EGE
Oil				
- OIP	X	X		X
- OIS	X	X		X
NGA				
- NGP	X	X		X
- NGS	X	X		X
SLD				
- COA	X	X		X
- BMT	X	X		X
NUE				X
REL				
- HYD				X
- SLE				X
- NUB				X
RNE				
- SLT	X	X		X
- NUN	X	X		
TEG				X
TPE	X	X		

7. Emission Table

7.1. GHG Type: CO_2, CH_4, N_2O, CFC, SO_2, Others, EQV (CO_2 Equivalent)

CO_2: (MtonneC/yr) monitored

CH_4: (MtonneCH$_4$/yr) monitored

N_2O: (MtonneN/yr) monitored

CFC: (MtonneCFC/yr) not monitored

SO_2: (MtonneS/yr) not monitored

Others: not monitored

EQV(CO_2 Equivalent): not monitored

7.2. Emission Source (Emi_{Source}):

EUP: Energy Use and Production

- EIN: Industrial Sector
- ERE: Residential Sector
- ETR: Transport Sector

BIB: Biomass Burning

NAT: Nature

DEF: Deforestation

PRP: Production Process
FER: Fertilized Soil
GAG: Gain in Agriculture
RFI: Rice Fields
AWA: Animal Waste
LFI: Landfill
SEW: Sewage
TOT: Total

7.3. Species *versus* Emissions-Source Matching Matrix

Species/ Source	EUP	BIB	NAT	DEF	PRP	FER	EFE	GAG	FRI	AWA	LFI	SEW	TOT
CO_2	X				X								X
CH_4	X	X			X						X	X	X
N_2O	X				X								X
CFC													
SO_2													
EQV													

7.4. Basecase Tables

Figure 50 gives global emission rates for CO_2, CH_4, and N_2O; 13) regionally resolved results are available from the ERB model, but not reported here. The Species *versus* Emissions-Source Matching Matrix give above was completed based on the capabilities of the version (Version 4.1) of the ERB model used for this study.[48] The CO_2 emissions listed below are given according to the point of emission, emissions for CH_4 are listed according to source of emission, and N_2O emissions are given according to demand sector, all according to the format inherent to the version of the ERB model being used.

7.4.1. Carbon Dioxide (MtonneC/yr)

year	conv. oil	shale oil	synoil	coal	syngas	gas	flaring	total
1975	1911.	---	---	1529.	---	927.	69.8	4437.
1990	2430.	---	---	2082.	---	853.	25.7	5391.
2005	2348.	13.9	184.	1952.	1.	1172.	18.2	5689.
2020	2450.	28.2	231.	1047.	1.	1395.	15.1	5166.
2035	2515.	51.6	318.	722.	1.	1322.	15.6	4944.
2050	2286.	95.8	397.	509.	1.	1219.	20.1	4528.
2065	1227.	164.6	984.	467.	---	1155.	15.7	4014.
2080	808.	242.2	1358.	451.	---	1070.	11.9	3942.
2095	546.	342.2	1690.	454.	1.	997.	11.9	4040.

7.4.2. Methane (MtonneCH_4/yr)

year	coal prod'n	gas prod'n	gas venting	gas transm. & dist.	auto exhaust	biomass burning	land-fill	total
1975	16.76	4.23	22.0	13.53	0.63	8.44	61.34	126.92
1990	19.31	5.49	7.76	9.38	1.27	11.44	74.76	129.41
2005	19.93	7.55	5.76	13.06	1.38	15.19	83.29	146.16
2020	11.99	8.98	5.09	13.48	1.42	18.03	65.81	124.80
2035	9.85	8.51	6.04	11.82	1.46	19.82	56.87	114.36
2050	8.66	7.85	8.89	9.88	1.29	21.33	43.37	101.26
2065	14.08	7.43	5.55	8.14	.89	23.15	32.08	91.33
2080	17.63	6.89	4.67	6.74	.78	23.30	35.67	95.68
2095	2094	6.42	5.16	5.64	.73	22.86	39.68	101.43

7.4.3. Nitrous Oxide (ktonneN_2O/yr) 1990

	electrical power			end use			
year	oil	gas	coal	oil	gas	coal	total
1975	4.7	5.2	52.1	23.2	4.1	48.2	137.6
1990	6.0	9.0	101.4	48.6	2.8	50.9	218.6
2005	3.2	12.1	69.0	52.6	3.9	70.6	211.5
2020	4.4	17.1	61.5	55.8	4.0	49.7	192.4
2035	5.3	17.6	55.5	59.7	3.5	38.2	179.7
2050	6.0	17.6	52.0	60.8	2.8	29.3	168.5
2065	5.8	18.3	46.1	57.7	2.3	23.6	153.8
2080	6.5	18.0	44.1	60.4	1.9	22.0	153.0
2095	7.7	17.7	43.9	65.1	1.6	22.2	158.2

8. Consequence Table

The consequences of the emissions listed above are evaluated only for CO_2 emissions. No attempts have been made to compute the equivalency term, EQV. The consequences are presented in terms of the temporal evolution of atmospheric CO_2 inventories, W(GtonneC), and average global temperature rise, ΔT(K); the conversion to ppmv is given by 2.13 GtoneC/ppmv. As described in the main body of this report, the integral-response model described in Ref. 15 has been incorporated into the ERB model to relate the above-listed emission rates to atmospheric accumulations and average global temperature rises. Figure 51 gives the time dependence of the CO_2 emission rate, R_{CO_2} (GtonneC/yr), the integrated emissions relative to the base year t_{IRV} = 1800 (when W_{IRV} = 594 GtonneC, IRV = industrial revolution), W_o(Gtonne), the evolving atmospheric inventory, W(Gtonne), and the ensuing global temperature rise, ΔT(K) measured from t_{IRV} = 1800. The following table lists the evolution of W and ΔT for the basis case being presented (*e.g.*, carbon tax rate of 40 $/tonneC/15yr and an AEEI parameter of ε_k = 0.0125 1/yr).

year	W(Gtonne)	ΔT(K)[a]
1975	779.5	0.44 (0.44)
1990	829.6	0.57(0.57)
2005	883.0	0.71(0.71)
2020	930.0	0.84 (0.98)
2035	969.5	0.96(1.09)
2050	1002.5	1.06(1.33)
2065	1028.2	1.14 (1.63)
2080	1049.8	1.21 (2.01)
2095	1069.6	1.27(2.28)

(a) values in parentheses correspond to no-carbon-tax, ε_k = 0.0100 1/yr Basis Scenario

FIGURES

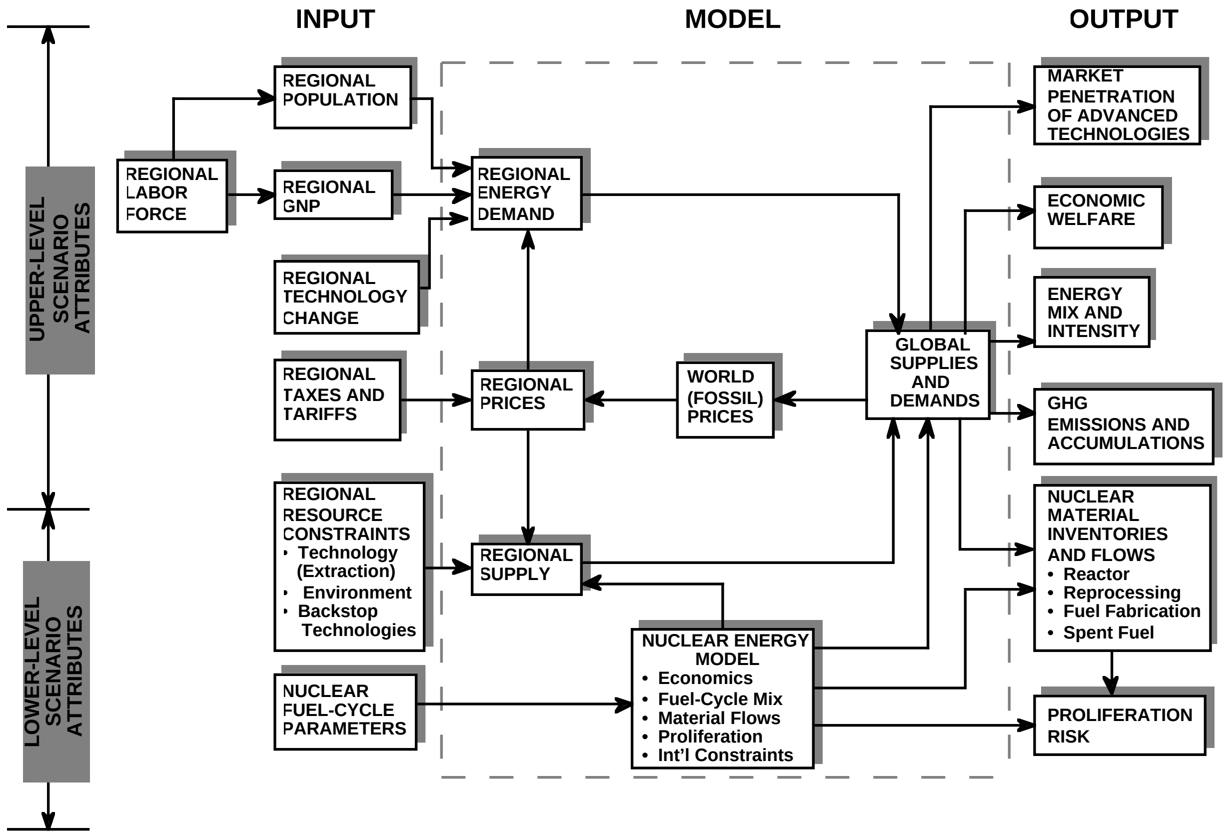


Figure 1. Structural layout of ERB global E^3 model[5] as adapted and modified for the present study. Four main components comprise the ERB economic-equilibrium model: energy demand; energy supply; energy balance; and greenhouse-gas (GHG) emissions. The relationships between inputs and interated outputs, as well as the addition of a (higher fidelity) nuclear energy model (resources, costs, nuclear-materials flows and inventories, and proliferation risk) are also shown.

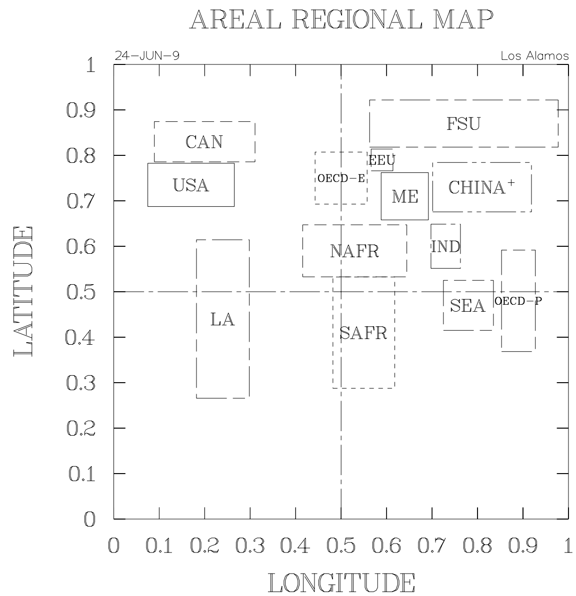


Figure 2. Schematic map of thirteen-region ERB model, with area of each stylized rectangular region reflected the respective land masses (Table I).The following regional identifiers are used: 1) USA = United States of America; 2) CAN = Canada; 3) OECD-E = OECD-Europe; 4) OECD-P = OECD-Pacific; 5) EEU = Eastern Europe; 6) FSU = Former Soviet Union; 7) $CHINA^+$ = China; 8) ME = Middle East; 9) NAFR = North Africa; 10) SAFR = Southern Africa; 11) LA = Latin America; 12) IND = India; and 13) SEA = South and East Asia.

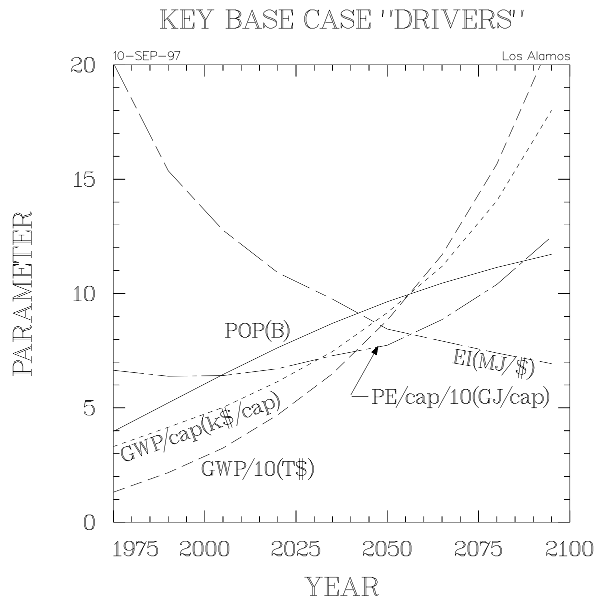


Figure 3A. Key base-case aggregated drivers and related first responses: Time dependencies of populations (exogenous); GWP (price-adjusted basis case); GWP/POP (price-adjusted basis case); primary-energy intensity, EI = PE/GWP(endogenous), and *per-capita* primary energy, PE/POP(endogenous).

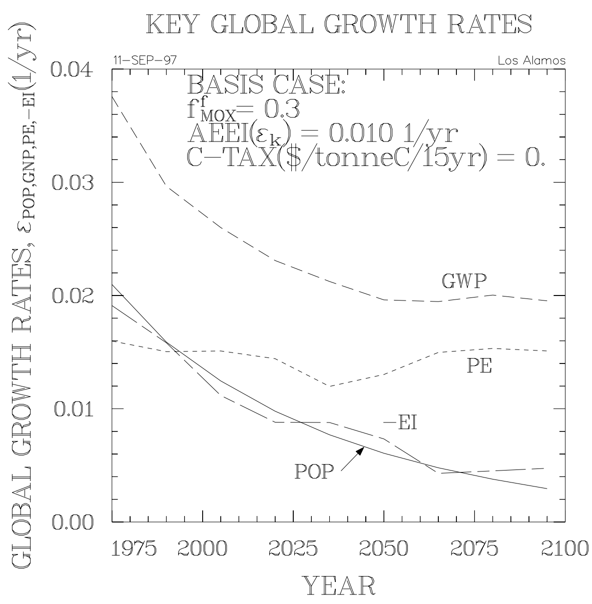


Figure 3B. Key base-case aggregated drivers and related first responses: Aggregated growth rates for population (exogenous); GWP (price-adjusted basis case; primary energy, PE(endogenous); and primary-energy intensity, EI = PE/GWP(endogenous).

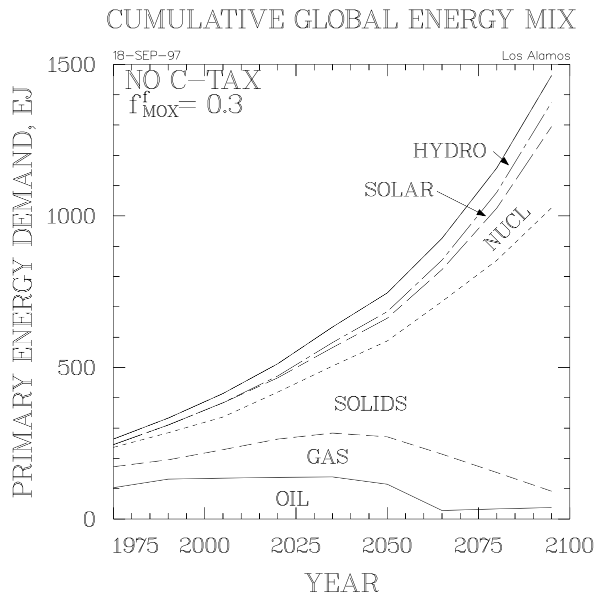


Figure 4A. Cumulative evolution of global primary energy mix for the Basis Scenario (solids = coal + biomass): Cumulative primary energy.

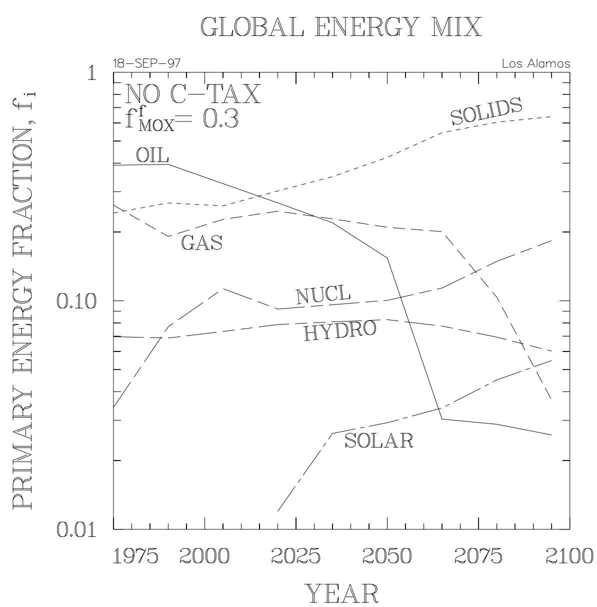


Figure 4B. Cumulative evolution of global primary energy mix for the Basis Scenario (solids = coal + biomass): Primary energy fractions.

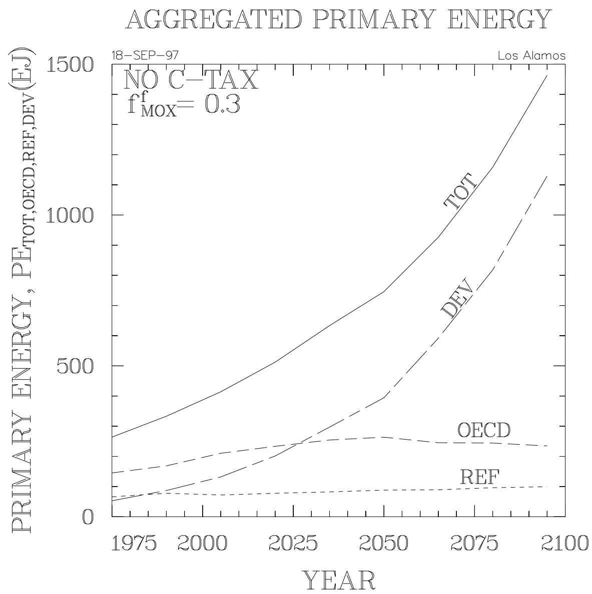


Figure 5. Evolution of aggregated total primary energy for Basis Scenario: OECD = US + CAN + OECD-E + OECD-P; REF = FSU + EEU; and DEV = CHINA+ + ME + NAFR + SAFR + L:A + IND + SEA.

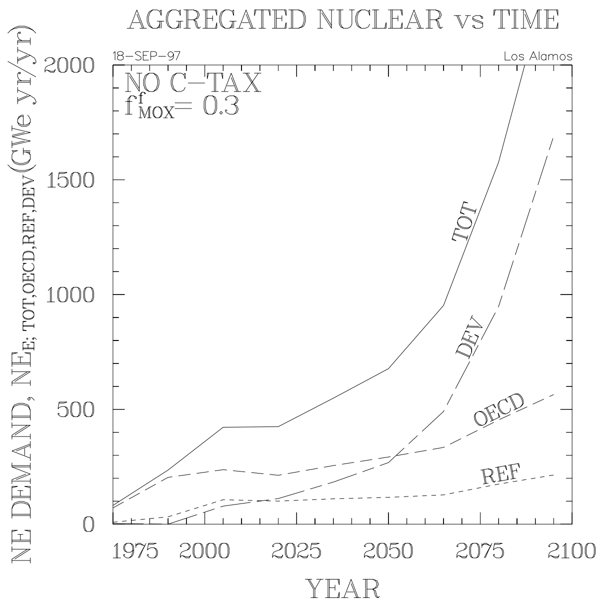


Figure 6A. Aggregated and (13) regional nuclear energy demand for the Basis Scenario: Aggregated total and macro-regional nuclear energy demand.

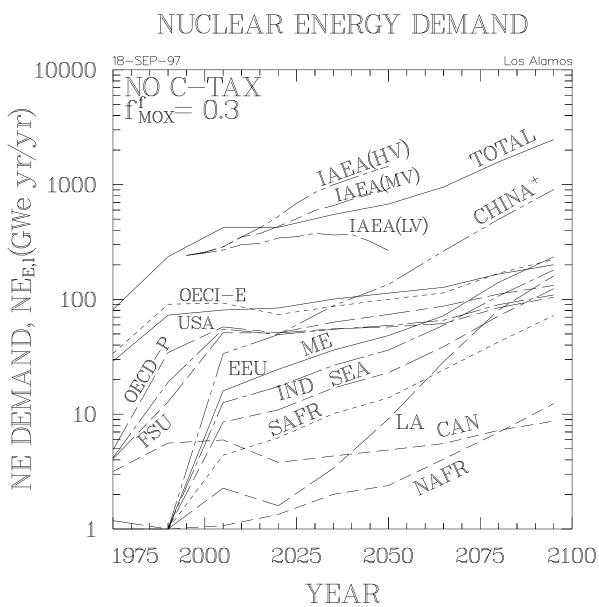


Figure 6B. Aggregated and (13) regional nuclear energy demand for the Basis Scenario: Regional nuclear energy demand.

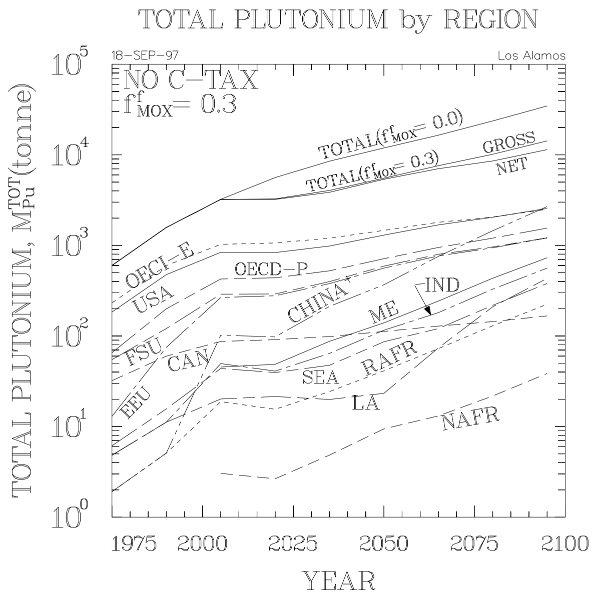


Figure 7. Region breakout of total accumulated plutonium for the Basis Scenario.

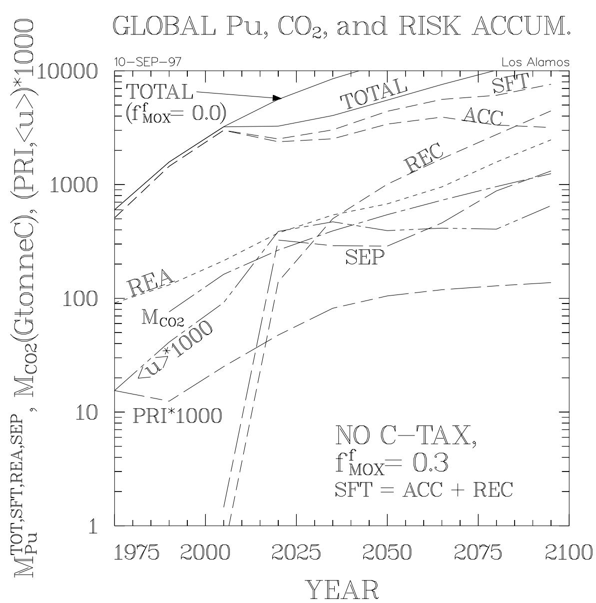


Figure 8. Plutonium and atmospheric carbon accumulations for the Basis Scenario. Spent-fuel plutonium is accumulated in two forms: recyclable (ACC) and fully recycled (REC); for the once-through LWR basis case, M_{Pu}^{REC} is negligible; average plutonium contained in LWRs is M_{Pu}^{REA}; measures of proliferation risk are expressed in terms of a relative proliferation utility, <u>, and a discounted sum of proliferation utilities or a proliferation risk index, PRI.[7,10].

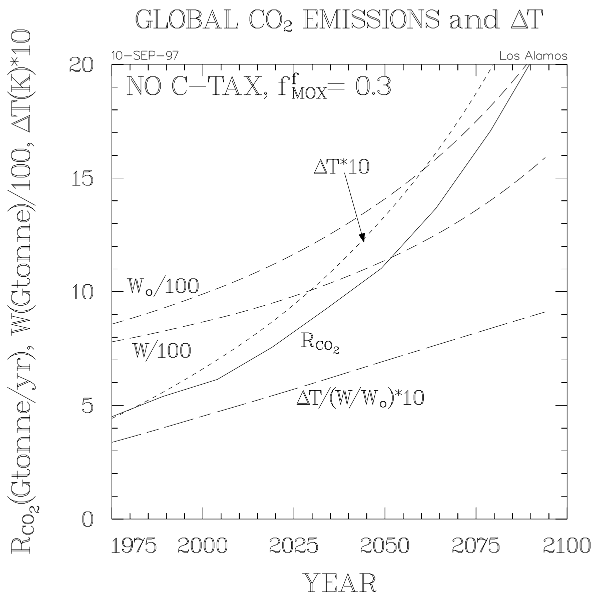


Figure 9. Time dependence of total CO_2 (carbon) emission, integrated emissions, atmospheric accumulation of emissions, and corresponding global average temperature rise, as determined from the linear integral-response model;[15,16] results applied to the zero carbon-tax basis case.[24]

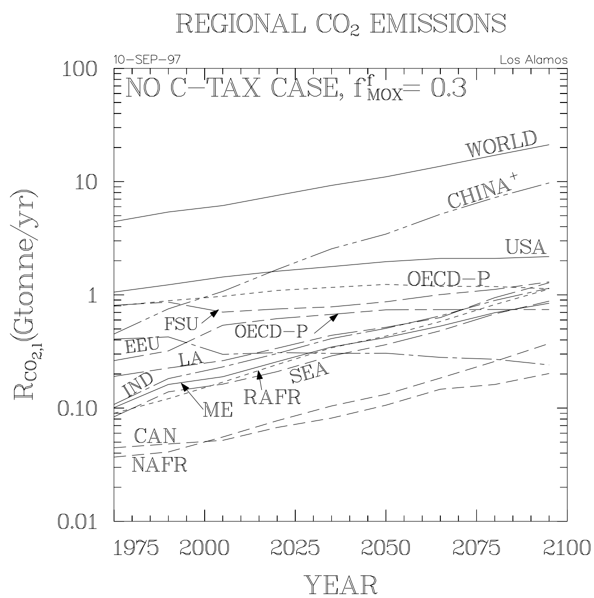


Figure 10. Atmospheric carbon emission rates as a function of time and region for Basis Scenario.

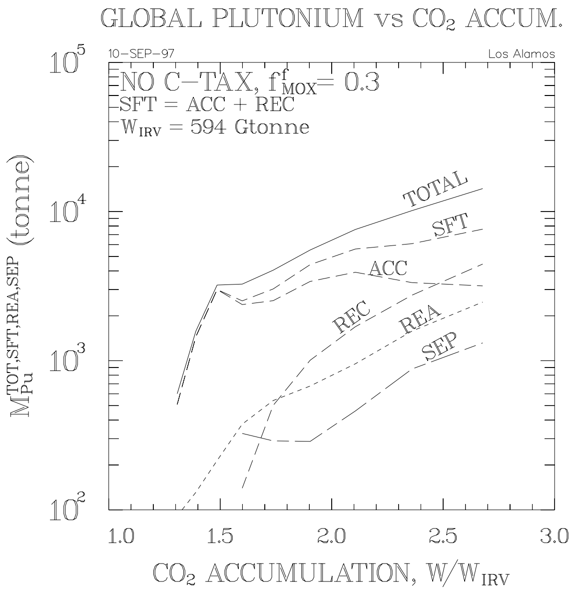


Figure 11A. Correlation of proliferation-risk index for no carbon taxes with atmospheric CO_2 (carbon) accumulation relative to pre-industrial levels (W_{IRV} = 594 Gtonne).

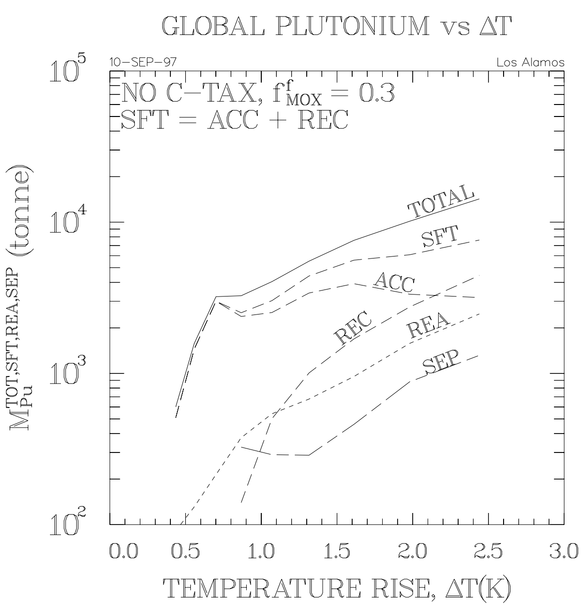


Figure 11B. Correlation of proliferation-risk index for no carbon taxes with average global temperature rise.

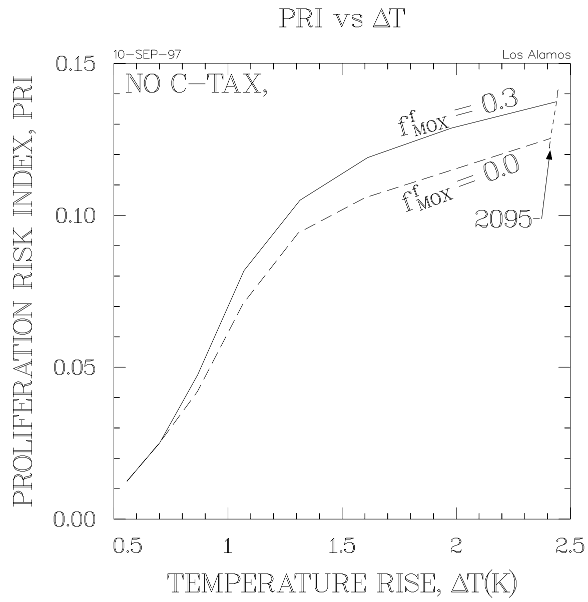


Figure 12. Correlation of proliferation-risk index with average global temperature rise for case without carbon tax imposed; comparison of PRI impacts of plutonium recycle (*e.g.*, f^{f}_{MOX} = 0.0 *versus* 0.30) is shown.

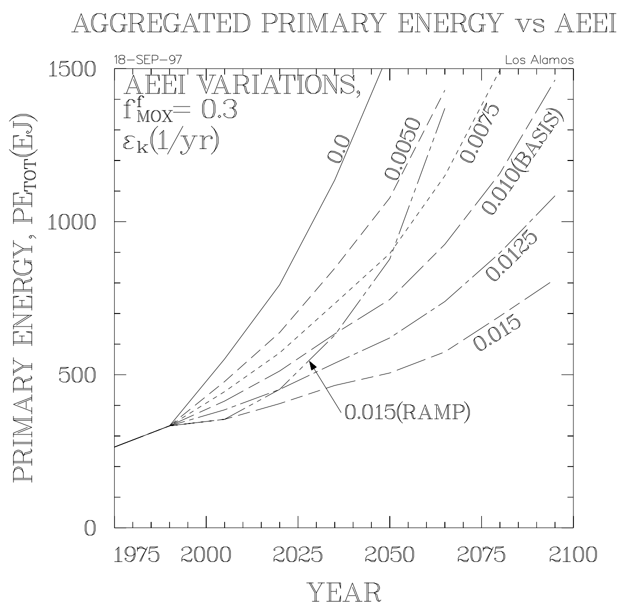


Figure 13. Primary energy demand as a function of time and AEEI; the ε_k = 0.015(RAMP) case starts ramping from the indicated value in 2005 and linearly decreases to zero by 2095.

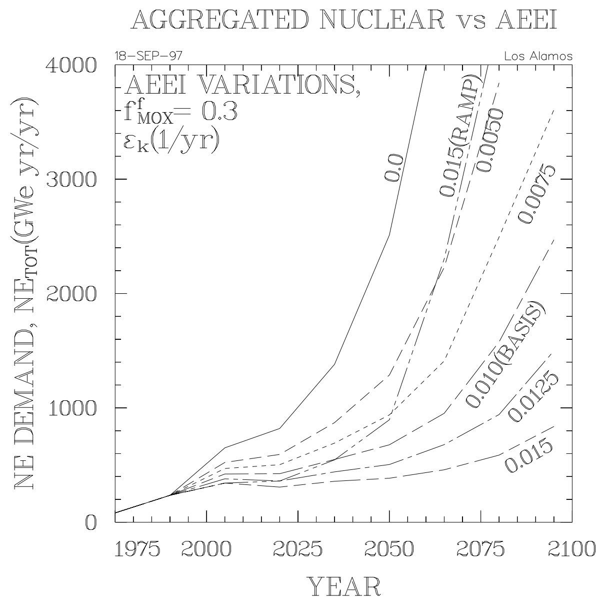


Figure 14. Nuclear energy demand as a function of time and AEEI; the ε_k = 0.015(RAMP) case starts ramping from the indicated value in 2005 and linearly decreases to zero by 2095.

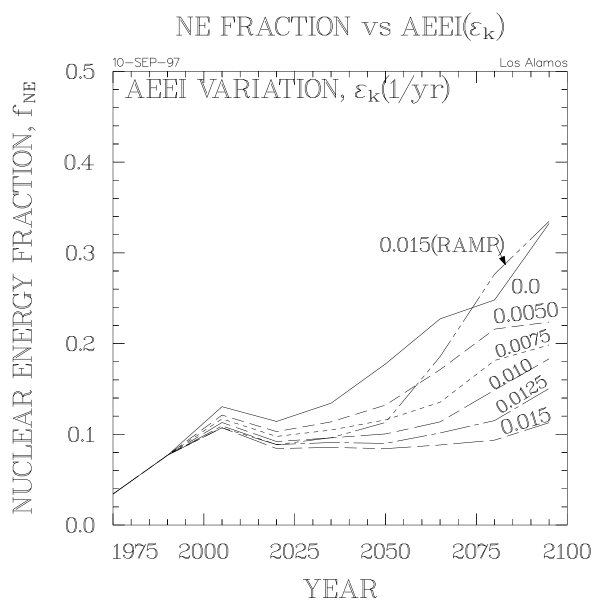


Figure 15. Nuclear energy as a fraction of total primary energy (same basis) as a function of time and AEEI; the ε_k = 0.015(RAMP) case starts ramping from the indicated value in 2005 and linearly decreases to zero by 2095.

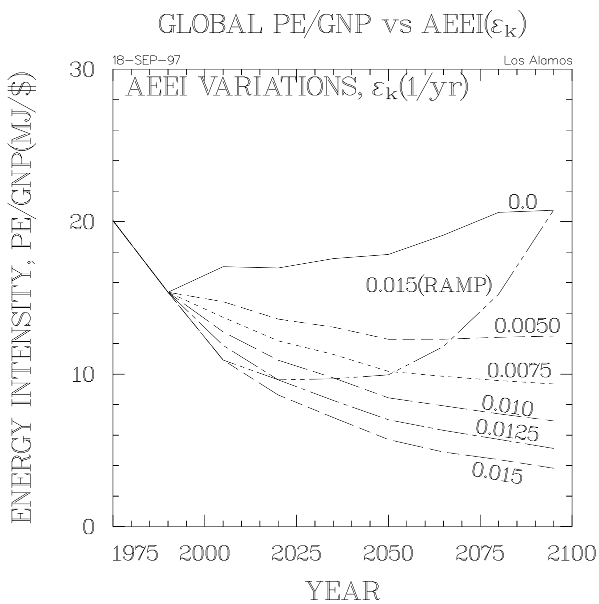


Figure 16. Primary energy intensity, EI = PE/GWP, as a function of time and AEEI; the ε_k = 0.015(RAMP) case starts ramping from the indicated value in 2005 and linearly decreases to zero by 2095.

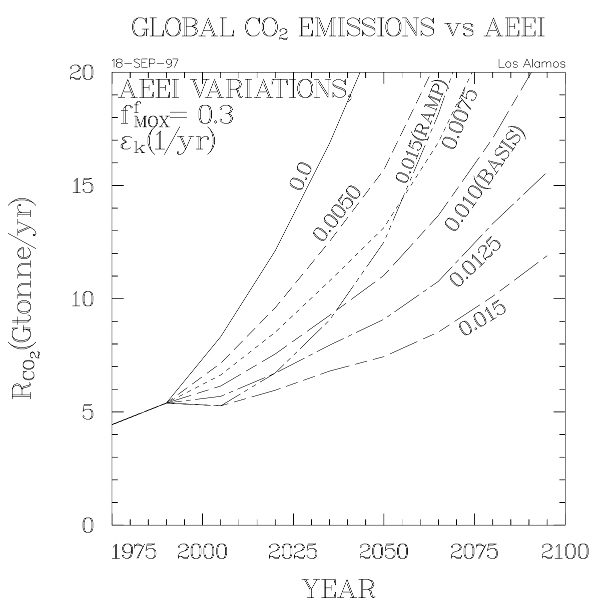


Figure 17. Carbon-dioxide (carbon) emission rate as a function of time and AEEI; the ε_k = 0.015(RAMP) case starts ramping from the indicated value in 2005 and linearly decreases to zero by 2095.

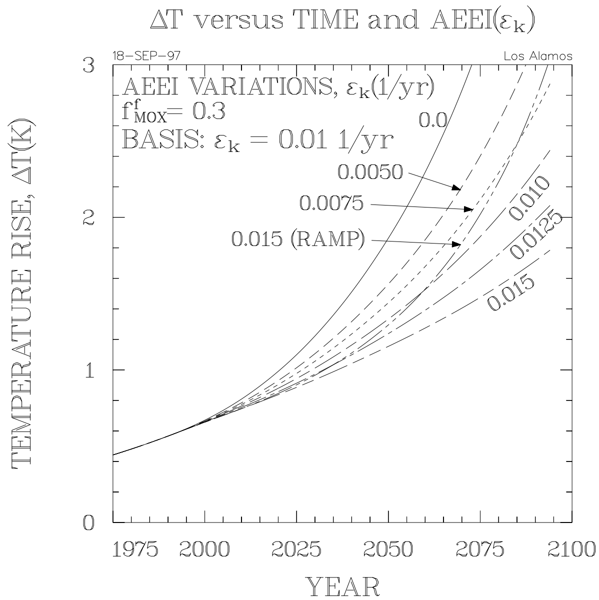


Figure 18. Average global temperature rise as a function of time and AEEI; the ε_k = 0.015(RAMP) case starts ramping from the indicated value in 2005 and linearly decreases to zero by 2095.

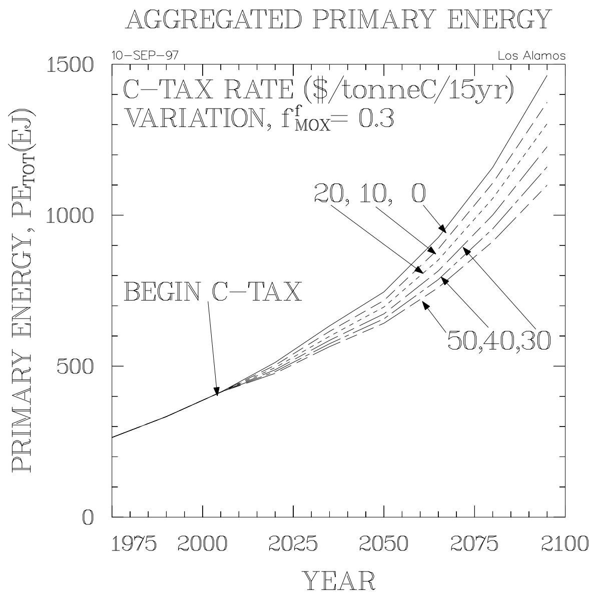


Figure 19. Primary energy demand as a function of time and carbon tax rate, starting in 2005.

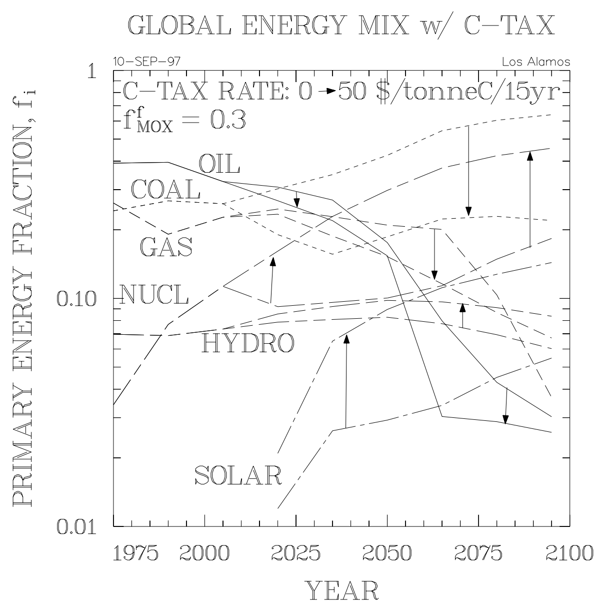


Figure 20. Shift in primary energy mix from Basis Scenario to strong carbon tax rate (50 $/tonneC/15yr, starting in 2005)

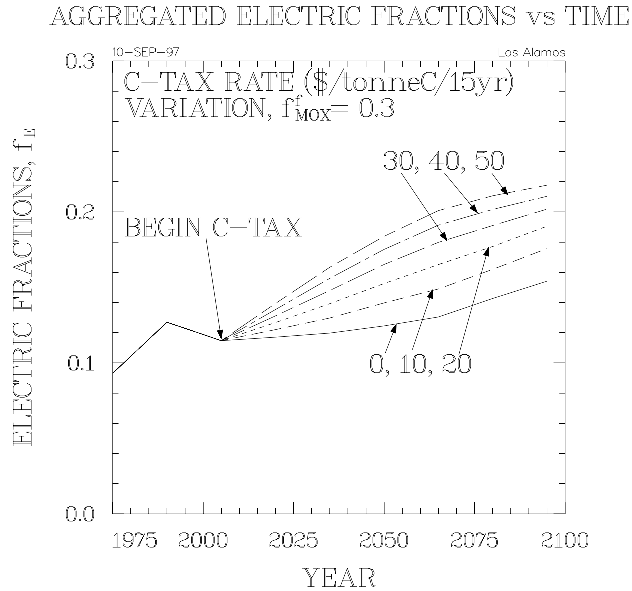


Figure 21. Fraction of total primary energy supplied by electricity as a function of time and carbon tax rate, starting in 2005.

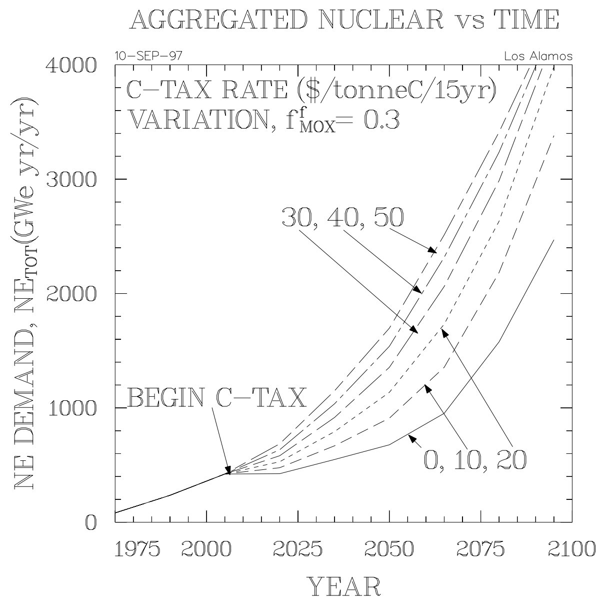


Figure 22. Nuclear energy demand as a function of time and carbon tax rate, starting in 2005.

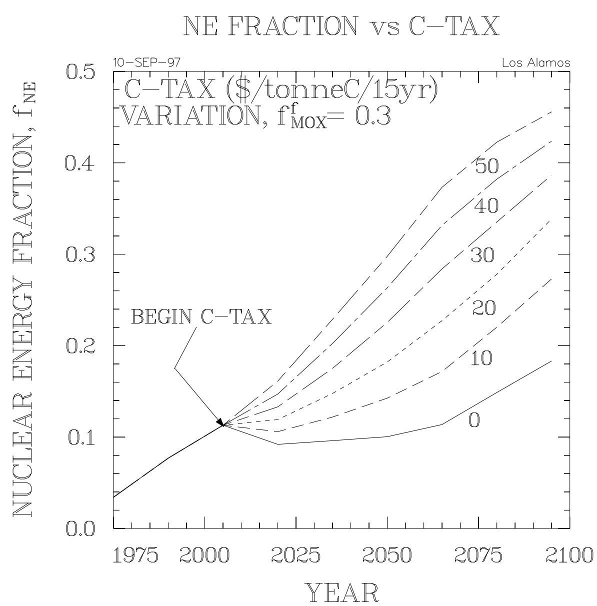


Figure 23. Nuclear energy as a fraction of total primary energy as a function of time and carbon tax rate, starting in 2005.

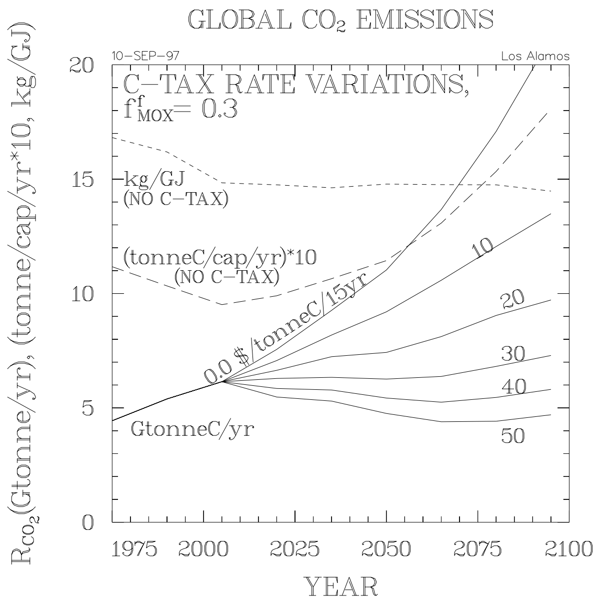


Figure 24A. Atmospheric carbon emission rates as a function of time and carbon tax rate, beginning in 2005; emission rates along with *per-capita* and per-primary-energy emissions for zero carbon taxes are shown.

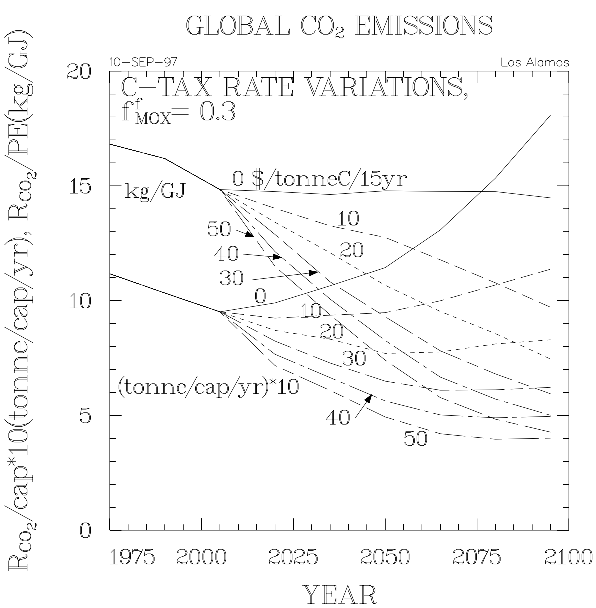


Figure 24B. *Per-capita* and per-primary-energy emissions for a range of carbon tax rates.

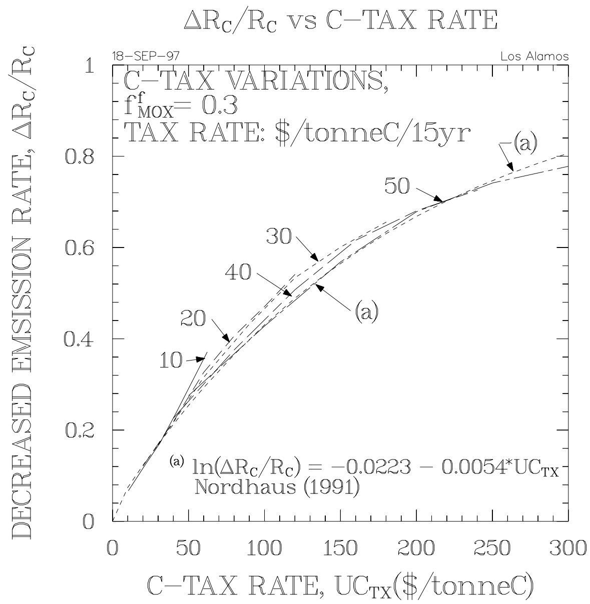


Figure 25. Decrease in atmospheric carbon emission rate as a function of carbon tax for a range of carbon tax rates; a regression fit to a number of model predictions[38] is also shown.

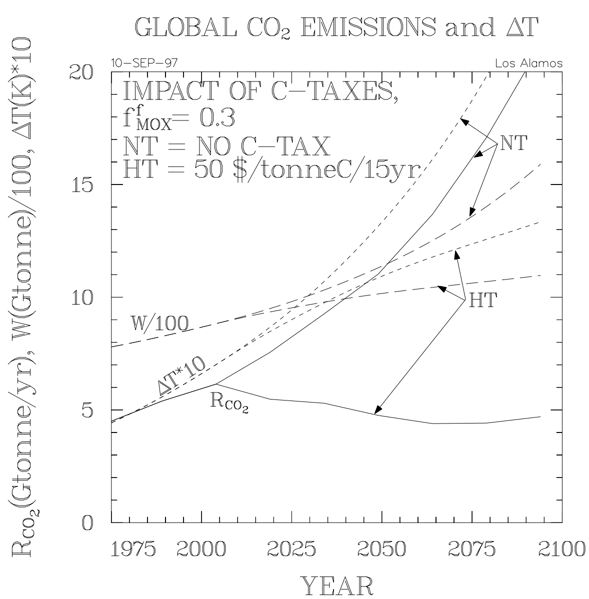


Figure 26. Impact of strong carbon-tax rate (50 $/tonneC/15yr) of atmospheric carbon emissions, accumulations, and associated average global temperature rise.

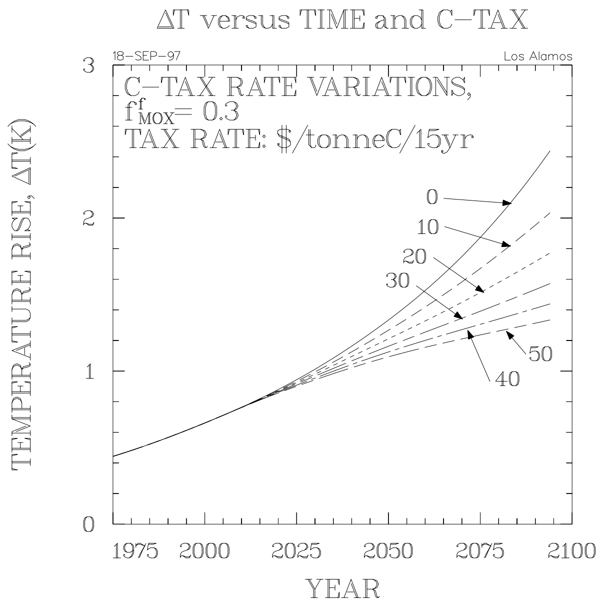


Figure 27. Time dependence of average global temperature rise for a range of carbon tax rates, starting in 2005.

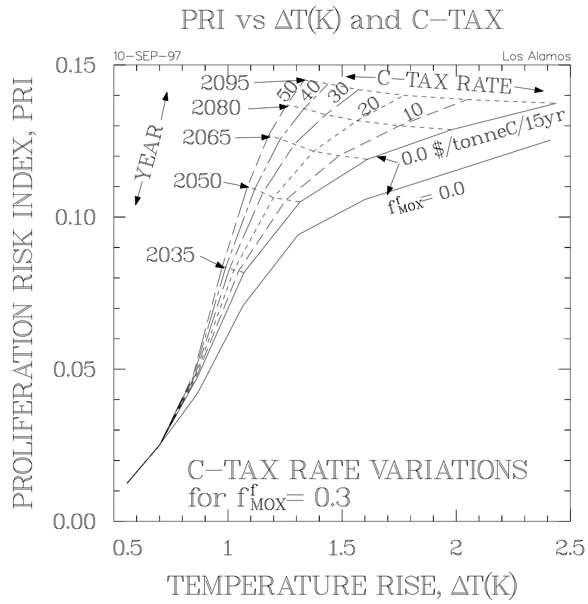


Figure 28A. Direct comparison of proliferation-risk-index *versus* atmospheric temperature-rise "operating curves" as the rate of carbon taxation is varied: direct comparison/ evolution of PRI *versus* ΔT, showing isochrones.

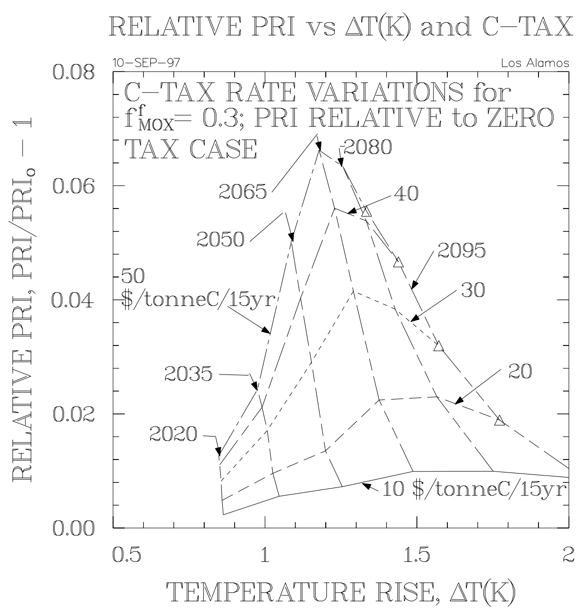


Figure 28B. Direct comparison of proliferation-risk-index *versus* atmospheric temperature-rise "operating curves" as the rate of carbon taxation is varied: change in PRI relative to the no-carbon-tax case, showing isochrones.

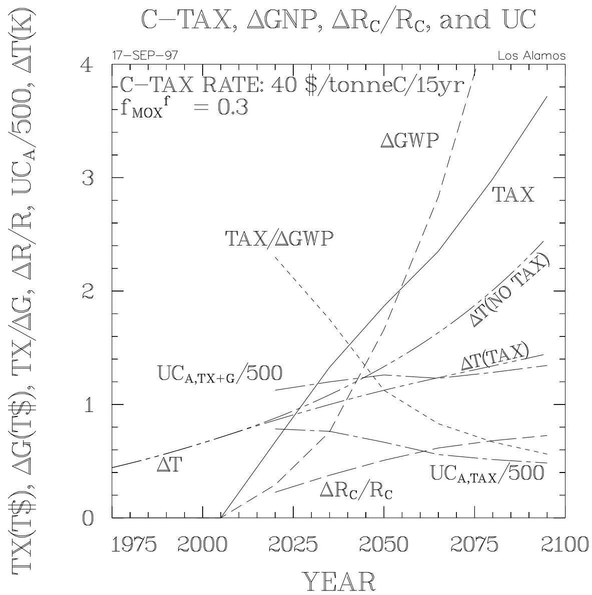


Figure 29. Time dependence of total carbon taxes, decreased GWP, tax-to-GWP ratio, percent decrease in atmospheric carbon emission rate, unit cost of CO_2 abatement, and average global temperature rise for a carbon tax rate of 40 \$/tonneC/15yr.

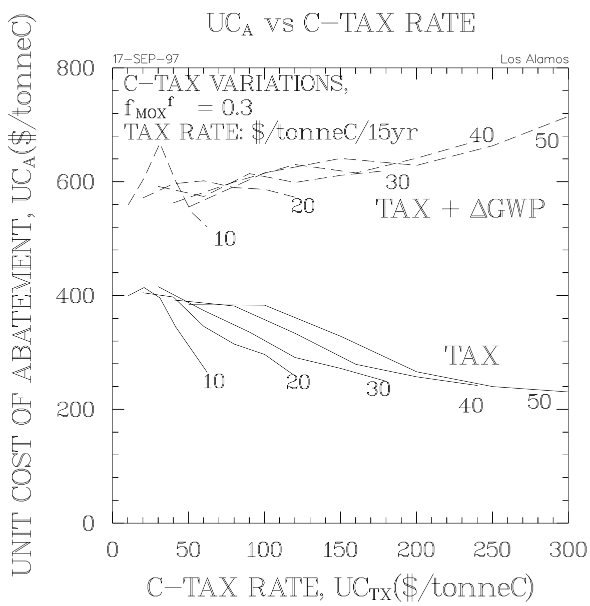


Figure 30. Dependencies of two measures of unit cost of abatement, UC_A(\$/tonneC), as a function of unit carbon tax, UC_{TX}(\$/tonneC), for a range of carbon tax rates (\$/tonneC/15yr).

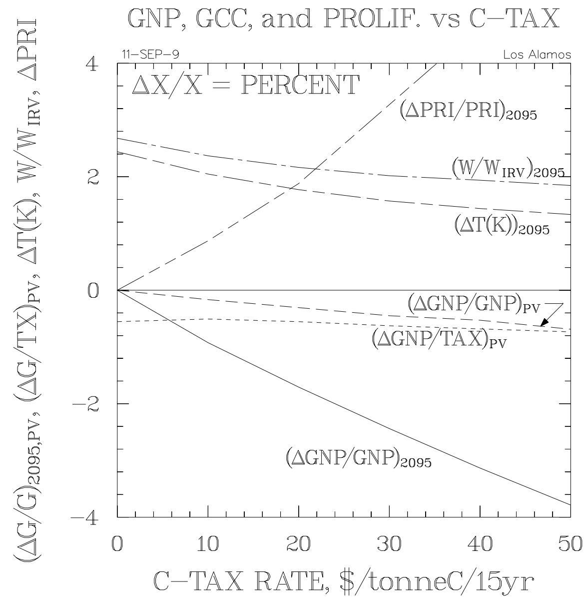


Figure 31A. Impact of carbon tax rates on either present value (PV) or last-year (2095) gross productivity (G = GWP), comparing GCC parameters (W/W_{IRV} and ΔT) with proliferation parameters (PRI); all relative changes $\Delta X/X$ are expressed as percentages: direct dependence on carbon tax rate.

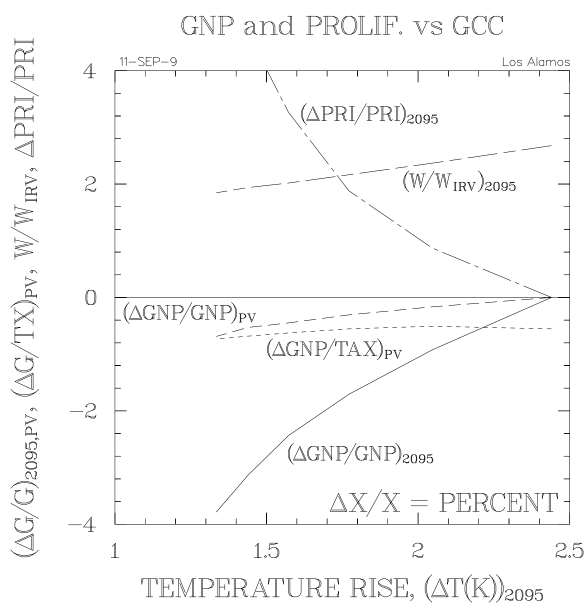


Figure 31B. Impact of carbon tax rates on either present value (PV) or last-year (2095) gross productivity (G = GWP), comparing GCC parameters (W/W_{IRV} and ΔT) with proliferation parameters (PRI); all relative changes $\Delta X/X$ are expressed as percentages. correlation with last-year (2095) temperature rise, as determined by carbon tax rate.

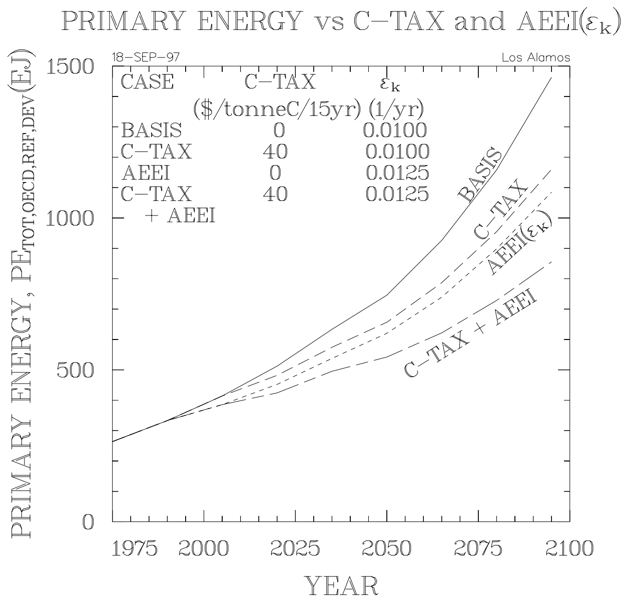


Figure 32. Primary energy demand as a function of time for a combination carbon tax rate and AEEI, showing relative impacts of supply-side (carbon tax) and demand-side (AEEI) scenario attributes.

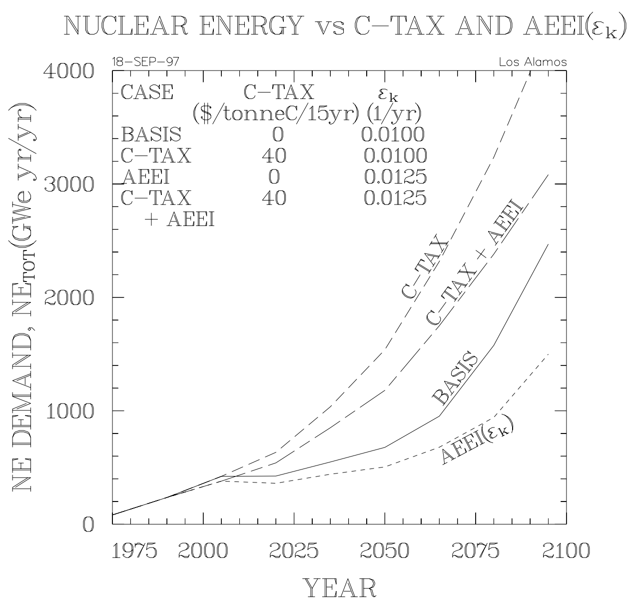


Figure 33. Nuclear energy demand as a function of time for a combination carbon tax rate and AEEI, showing relative impacts of supply-side (carbon tax) and demand-side (AEEI) scenario attributes.

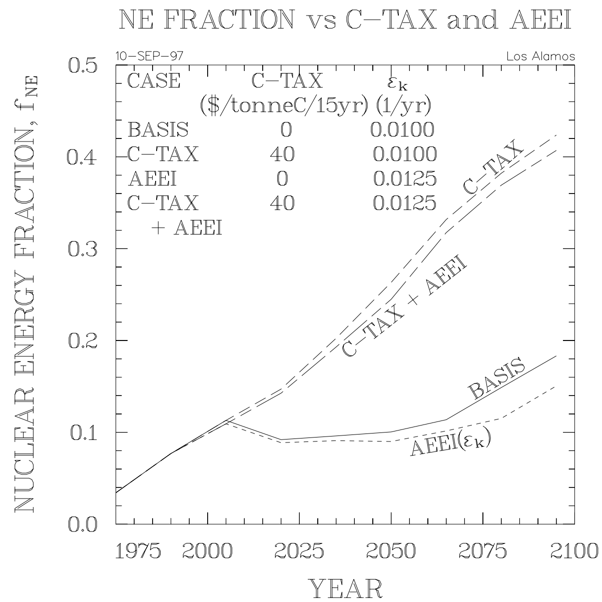


Figure 34. Nuclear energy fraction of primary energy (same basis) as a function of time for a combination carbon tax rate and AEEI, showing relative impacts of supply-side (carbon tax) and demand-side (AEEI) scenario attributes.

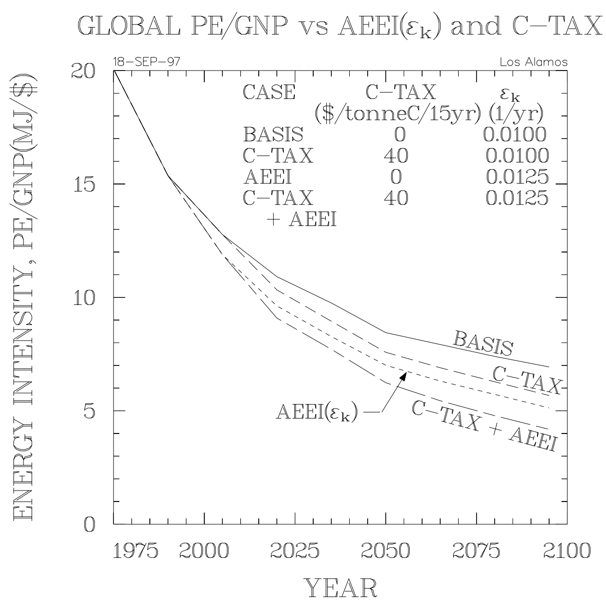


Figure 35. Primary energy intensity as a function of time for a combination carbon tax rate and AEEI, showing relative impacts of supply-side (carbon tax) and demand-side (AEEI) scenario attributes.

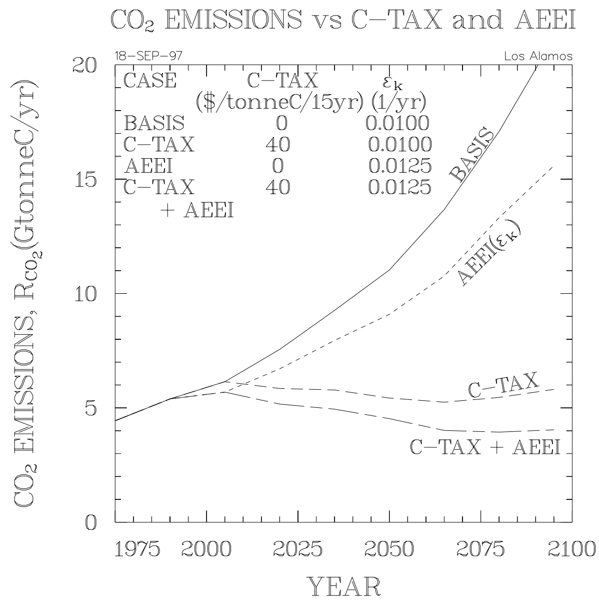


Figure 36. Emission rates of atmospheric carbon as a function of time for a combination carbon tax rate and AEEI, showing relative impacts of supply-side (carbon tax) and demand-side (AEEI) scenario attributes.

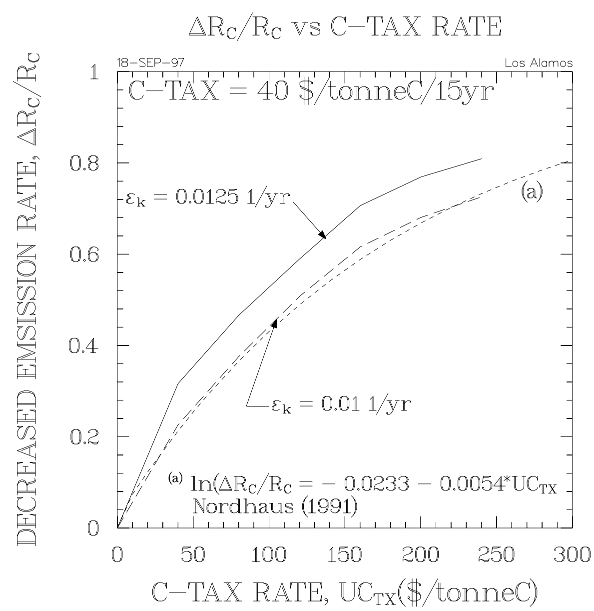


Figure 37. Impact of AEEI on effectiveness of carbon taxes in reducing emissions of atmospheric carbon for a carbon tax rate of 40 $/tonneC/15yr; shown also is a regression fit to a number of model predictions.[38]

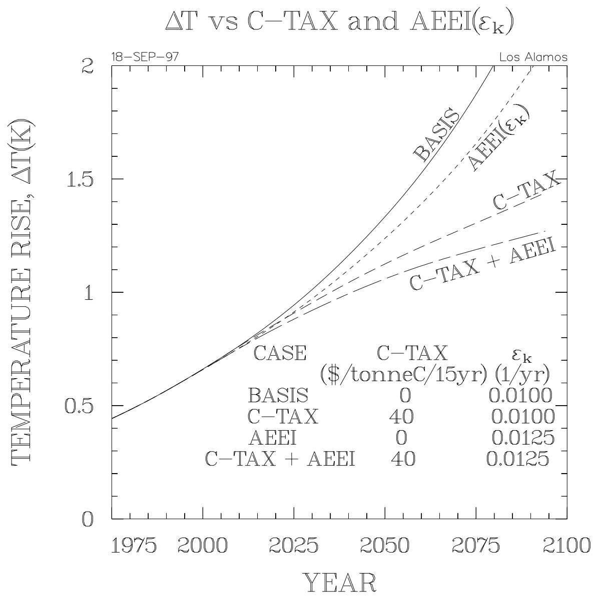


Figure 38. Average global temperature rise as a function of time for a combination carbon tax rate and AEEI, showing relative impacts of supply-side (carbon tax) and demand-side (AEEI) scenario attributes.

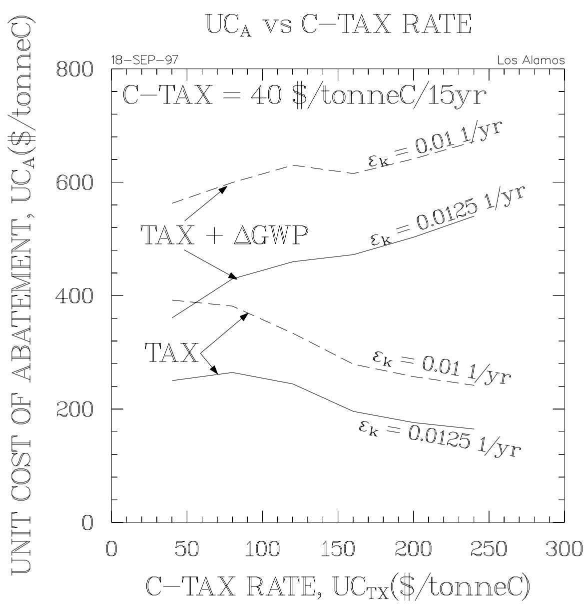


Figure 39. Impact of AEEI on relationship between unit carbon tax, UC_{TX}($/tonneC), and two measures of units costs of abatement, UC_A($/tonneC).

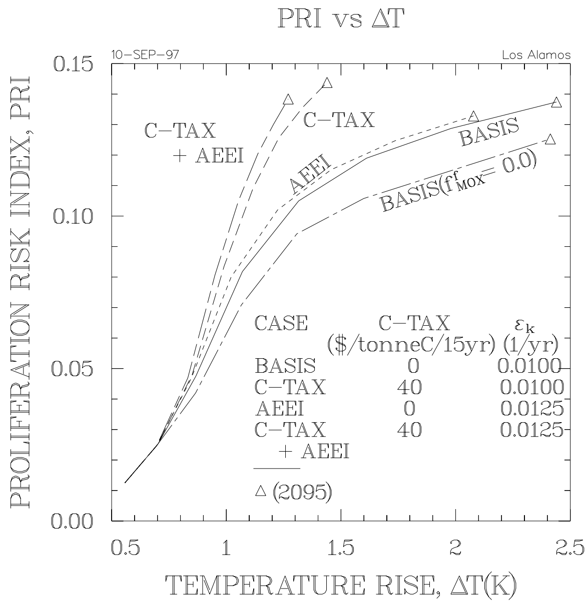


Figure 40. Direct comparison of proliferation-risk-index *versus* atmospheric temperature-rise "operating curves" for a combination carbon tax rate and AEEI, showing relative impacts of supply-side (carbon tax) and demand-side (AEEI) scenario attributes.

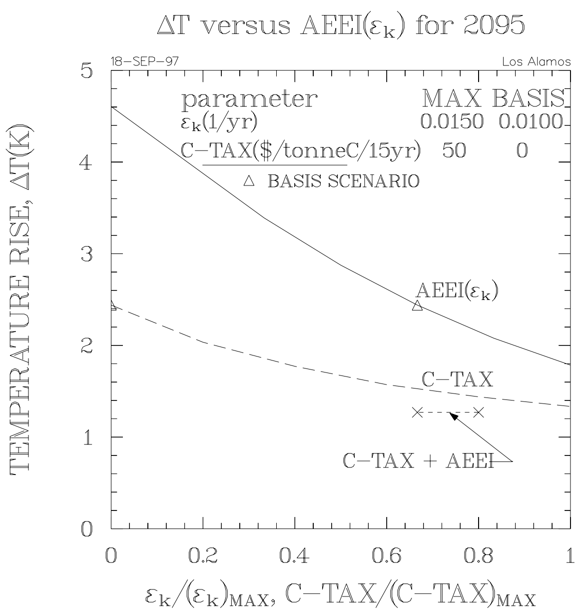


Figure 41. Global temperature rise as a function of relative changes in demand-side (ε_k) and supply-side (carbon tax rate) scenario attributes, with reference and basis-scenario values of each indicated; also shown is the combined AEEI + C-TAX case.

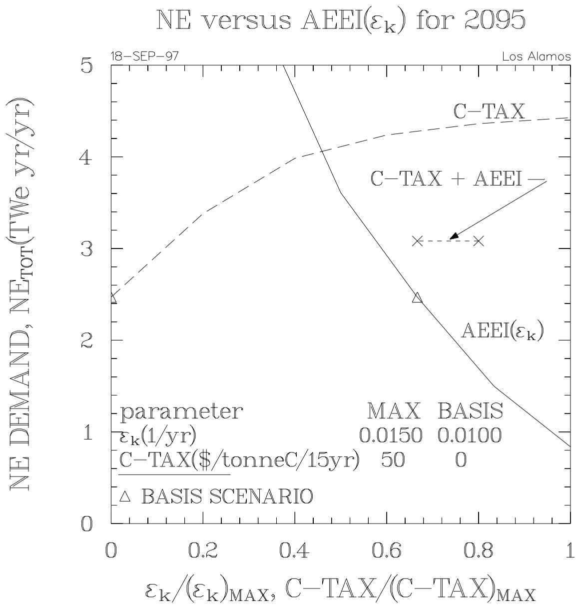


Figure 42. Nuclear energy demand as a function of relative changes in demand-side (ε_k) and supply-side (carbon tax rate) scenario attributes, with reference and basis-scenario values of each indicated; also shown is the combined AEEI + C-TAX case.

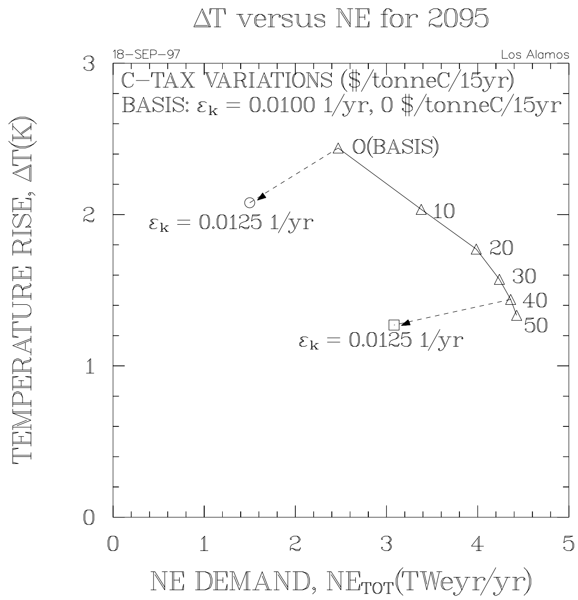


Figure 43A. Dependence of global temperature rise on carbon-tax-induced (supply-side) nuclear-energy demand, showing impact of demand-side increases in AEEI for the Basis Scenario (no carbon taxes) and for a case where the carbon tax is imposed at a rate of 40 $/tonneC/15yr.

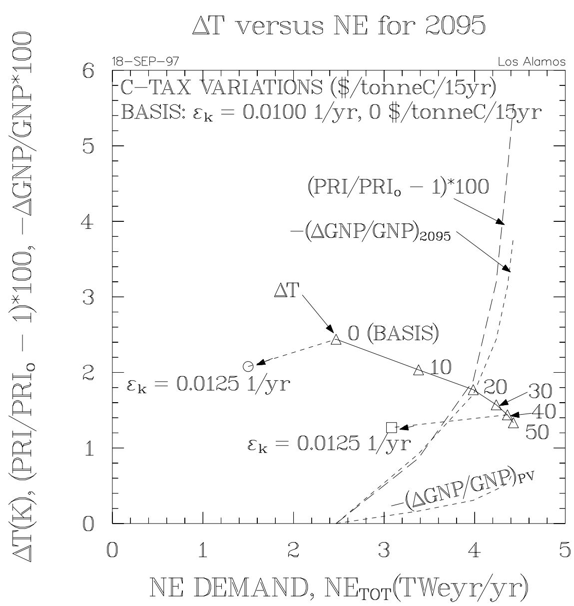


Figure 43B. Dependence of global temperature rise on carbon-tax-induced (supply-side) nuclear-energy demand, showing impact of demand-side increases in AEEI for the Basis Scenario (no carbon taxes) and for a case where the carbon tax is imposed at a rate of 40 $/tonneC/15yr; also shown is the increase in PRI relative to the Basis Scenario as well as the relative decrease in GNP.

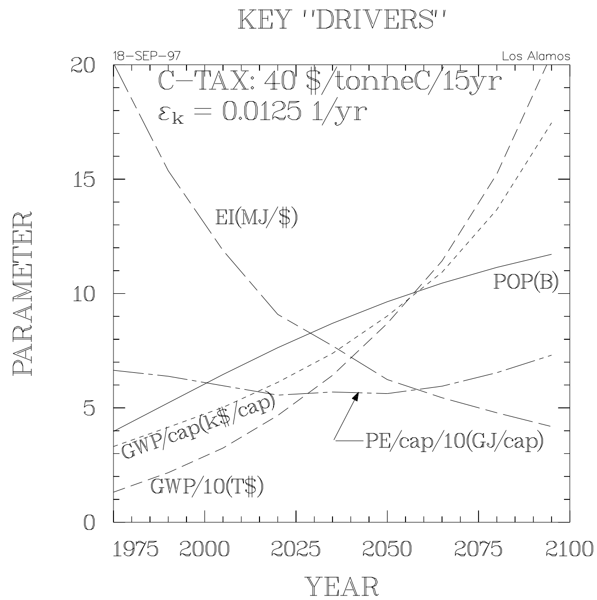


Figure 44. Key "drivers" and responses for the basecase GCC scenario.

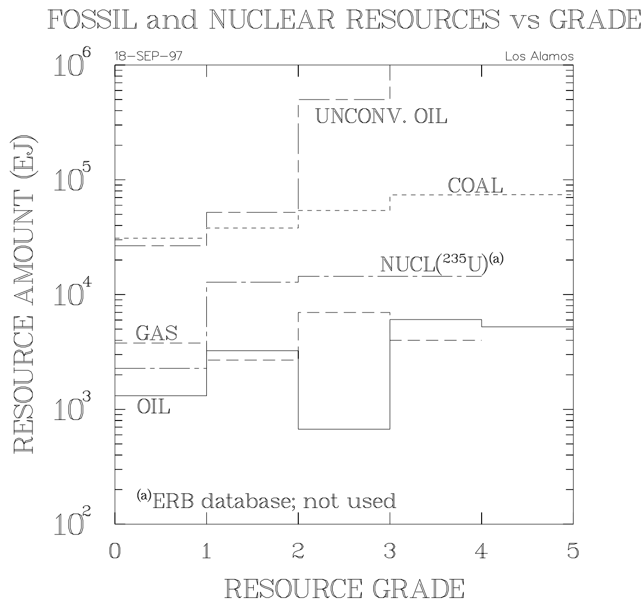


Figure 45A. Fossil energy resources used in the ERB model;[5] the uranium resource reported here has been replaced with that of Ref. 33: resource as a function of grade, per the Ref.-5 definitions.

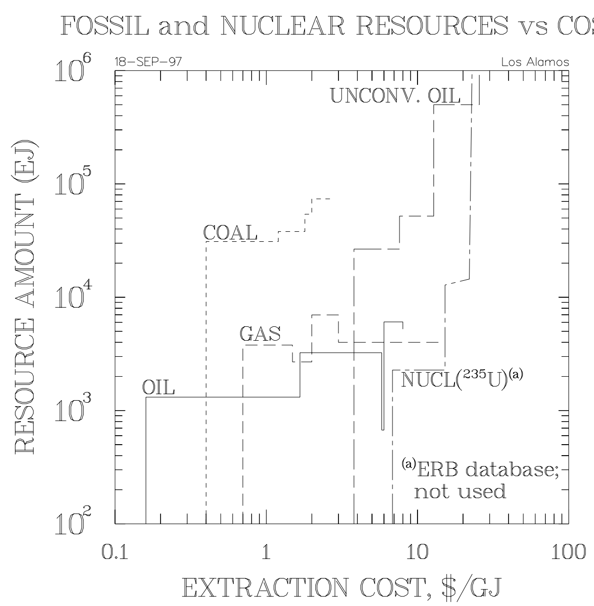


Figure 45B. Fossil energy resources used in the ERB model;[5]the uranium resource reported here has been replaced with that of Ref. 33: resource as a function of extraction cost, per the Ref.-5 definitions.

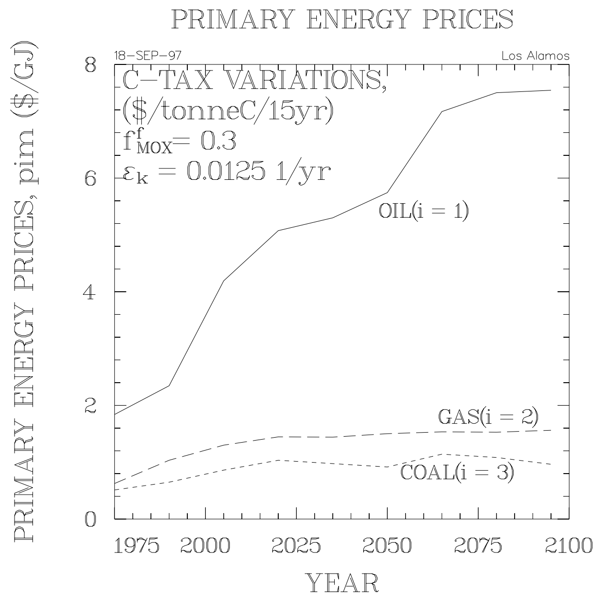


Figure 46. Primary fossil-energy world-market prices required for market-clearing for conditions describing the basecase GCC scenario.

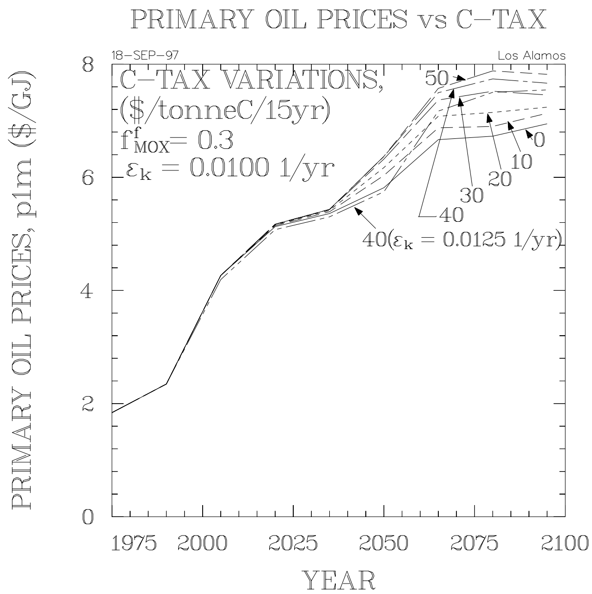


Figure 47A. Primary fossil-energy world-market prices required for market-clearing for a range of carbon-tax scenarios, as well as for the conditions describing the basecase GCC scenario: primary oil world-market-clearing prices.

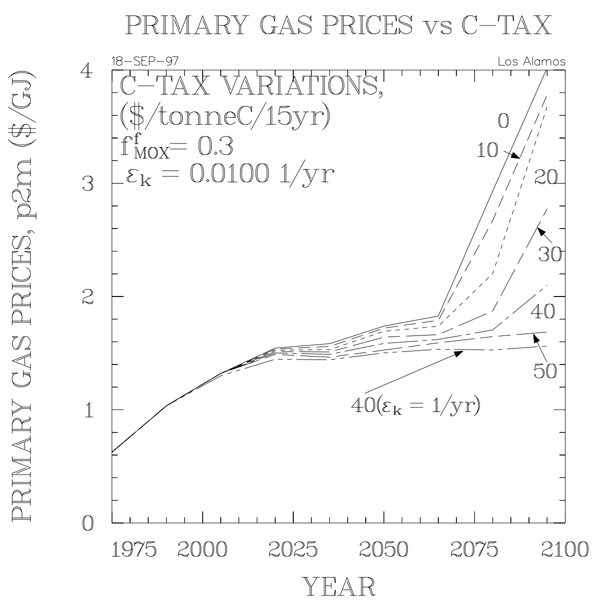


Figure 47B. Primary fossil-energy world-market prices required for market-clearing for a range of carbon-tax scenarios, as well as for the conditions describing the basecase GCC scenario: primary gas world-market-clearing prices.

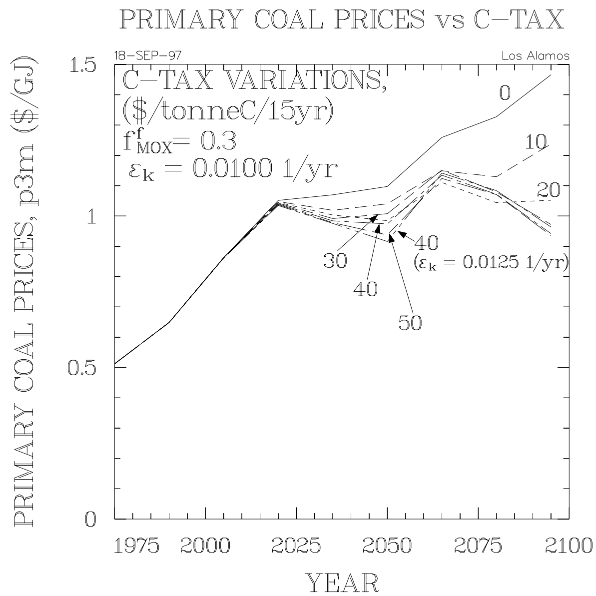


Figure 47C. Primary fossil-energy world-market prices required for market-clearing for a range of carbon-tax scenarios, as well as for the conditions describing the basecase GCC scenario: primary coal world-market-clearing prices.

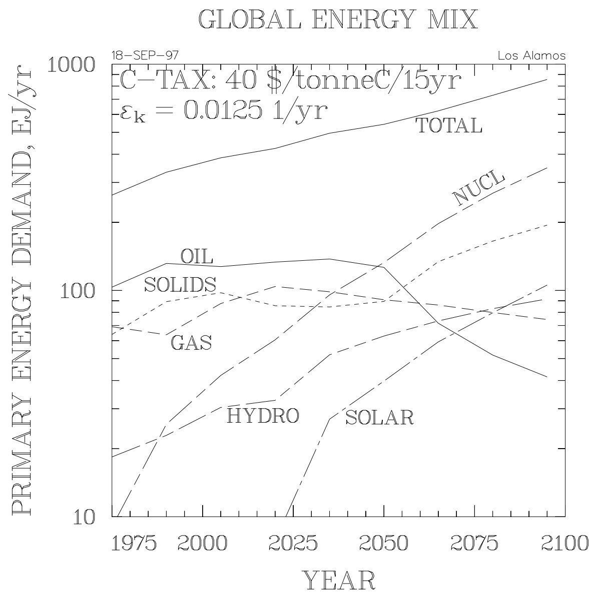


Figure 48A. Primary energy demand as a function of time: for basecase GCC scenario.

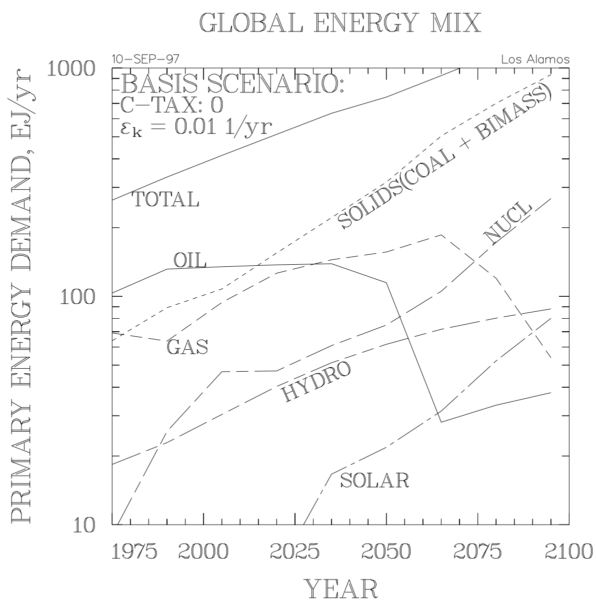


Figure 48B. Primary energy demand as a function of time: for Basis Scenario.

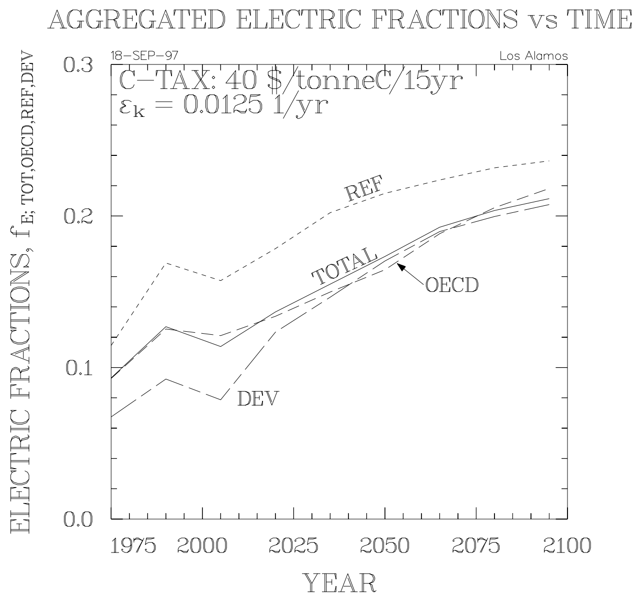


Figure 49. Electricity fractions (of primary energy) for the basecase GCC scenario, showing both total (World) and macro-regional dependencies (refer to Fig. 2 for regional and macro-regional notation).

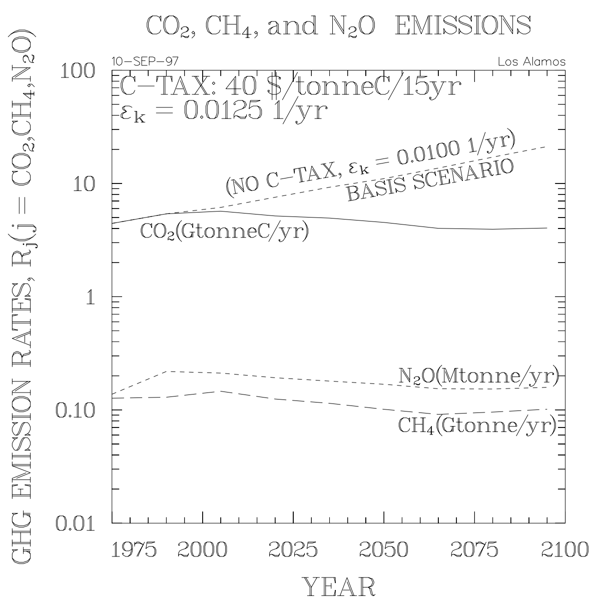


Figure 50. Emission rates for those GHGs considered by the ERB model for the basecase GCC scenario.

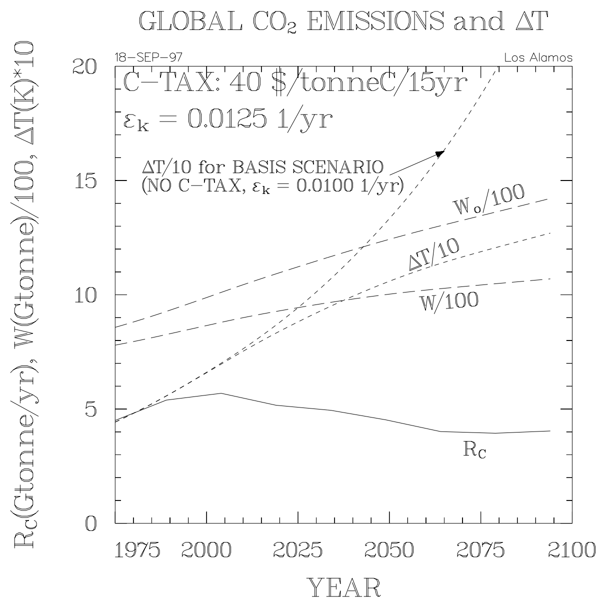


Figure 51. Consequences of the CO_2 emission rates reported on Fig. 50 for the basecase GCC scenario.

Table I. Thirteen Regions Described in ERB Model

ID	Region	Population (millions)		Linear	Land Area	Population	Nuclear Energy[44,45]	
		1990[41,42]	1995[42,42]	growth (%/yr)	(km^2)[42,43]	Density ($1/km^2$)	Capacity (Gwe, 1996)	Number
USA	United States of America	248.770(4.72%)	263.614	1.19	9,155,166(6.79%)[(a)]	27.17	99.0(28.9%)	109(26.6%)
CAN	Canada	26.647(0.51%)	28.435	1.34	9,971,875(7.40%)	2.67	15.4(4.5%)	22(5.4%)
OECD-E	OECD-Europe	434.008(8.22%)	449.568	1.34	6,665,284(4.94%)	65.07	122.5(14.0%)	133(14.9%)
OECD-P	OECD-Pacific	187.477(3.55%)	193.143	0.60	8,442,636(6.26%)	22.26	47.0(14.0%)	61(14.9%)
EEU	Eastern Europe	123.380(2.34%)	123.545	0.03	1,166,387(0.87%)	105.78	9.1(2.7%)	12(2.9%)
FSU	Former Soviet Union	289.921(5.50%)	297.507	0.52	21,819,782(16.18%)	13.28	35.1(10.2%)	48(11.8%)
CHINA[+]	China and environs	1,216.226(23.8%)	1,318.869	1.69	11,989,362(8.89%)	101.44	2.2(0.6%)	3(0.7%)
ME	Middle East	132.420(2.51%)	156.578	3.65	5,488,509(4.07%)	24.13	-- --	-- --
NAFR	North Africa	164.932(3.12%)	191.029	3.16	13,328,688(9.89%)	12.37	-- --	-- --
SAFR	Southern Africa	425.203(8.07%)	479.348	2.54	16,931,332(12.56%)	25.11	1.8(0.5%)	2(0.6%)
LA	Latin America	441.038(8.37%)	481.045	1.81	20,543,256(15.24%)	21.47	2.9(0.8%)	5(1.3%)
IND	India	846.191(16.05%)	936.546	2.14	3,183,643(2.36%)	265.79	2.5(0.7%)	10(2.5%)
SEA	South and East Asia	682.697(12.95%)	766.024	2.44	6,152,513(4.56%)	110.97	5.0(1.4%)	7(1.7%)
TOT	World	5271.338	5685.261	1.57	134,838,333[(b)]	39.09	342.5	412

(a) Based on total land area, less Antarctica (14,200,000 km^2)

(b) does not include 14,200,000 km^2 for Antarctica (5th largest continent), which, if included, gives a total land area of 149,000,000 km^2.