LA-UR-97-4891

Title:

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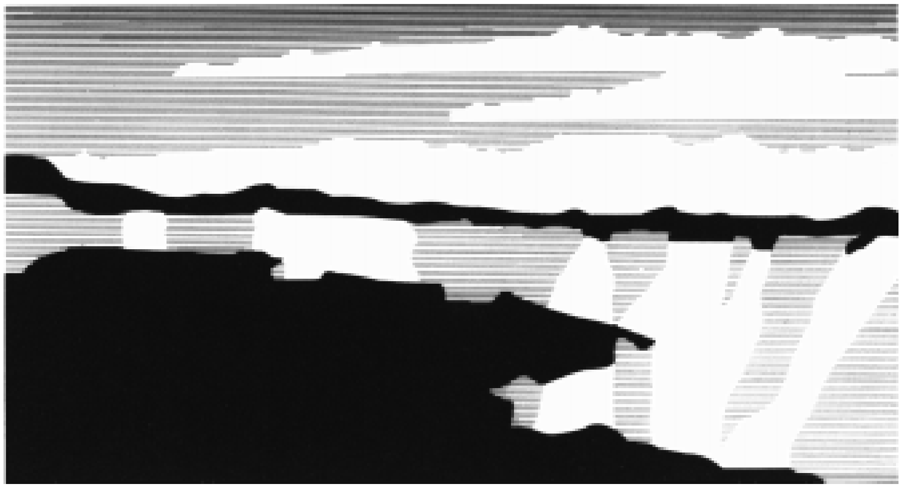
Submitted to:

International Conference on
Environment and Nuclear Energy

October 27-29, 1997



Los Alamos
NATIONAL LABORATORY

LA-UR-97-4891 December 12, 1997

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 tradeoffs 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) might 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 reduced- or non-carbon forms. In terms of stemming greenhouse warming for minimal cost of greenhouse-gas abatement, and within the limitations of the simplified taxing schedule used, a symbiotic combination of these two approaches may offer advantages not found if each is applied separately.

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] has been on issues and concerns related to global implementation of an expanding nuclear fuel cycle, the “top-down” behavioral model of an

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[*] The sampling of results presented herein is elaborated in Los Alamos National Laboratory document LA-UR-97-4380 (October 29, 1997) of the same authorship, title, and textual material.

equilibrium (*e.g.*, market-clearing, 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 surface temperature, $\Delta T(K)$. 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 remain 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 presently serves 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 might play in abating greenhouse warming. After giving a synoptic narrative describing the ERB model, results are presented according to 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. This "strawman" scenario combines both supply-side (carbon-tax induced increase in nuclear-energy demand) and demand-side (AEEI increases) approaches. An interim summary and conclusions follows.

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 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 adequately targets the 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 oxidized and 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 renewables; 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 primary electrical energy 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 (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 of three energy-service groups 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.

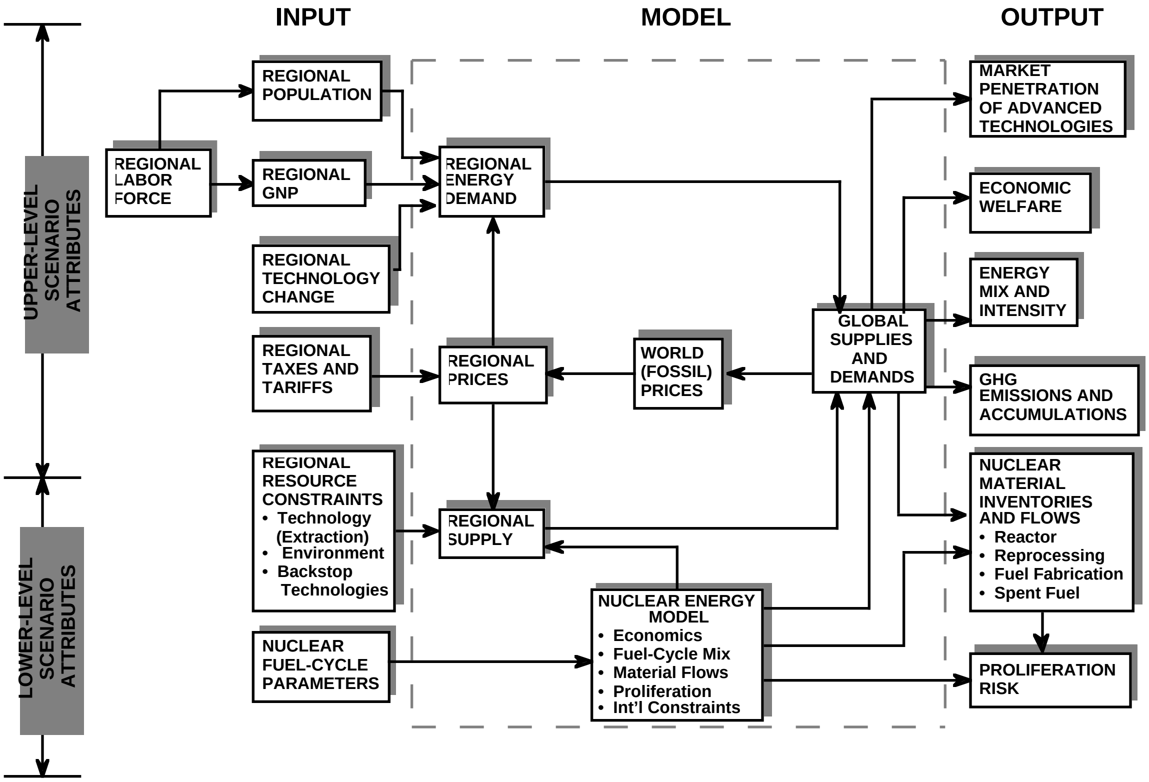

Figure 1. Structural layout of ERB global E^3 model[5] as adapted and modified for the present study. Four main components comprise the ERB economic-equilibrium model: energy demand; energy supply; energy balance; and greenhouse-gas (GHG) emissions. The relationships between inputs and interated outputs, 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.

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 × 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 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 provided 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, 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. 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.

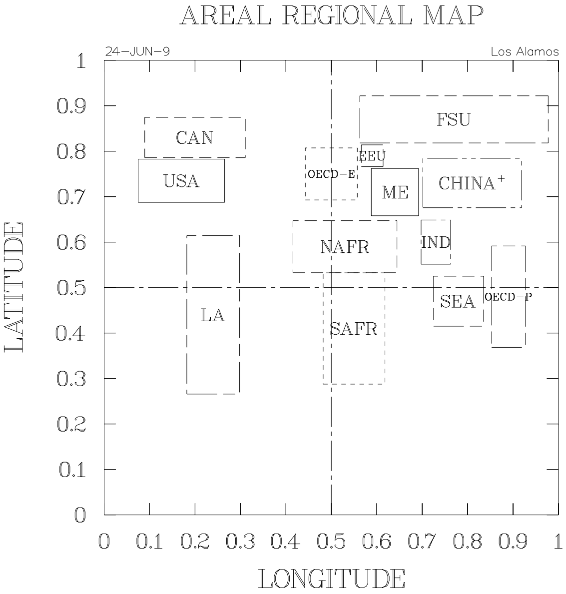

Figure 2. Schematic map of thirteen-region ERB model, with area of each stylized rectangular region reflected the respective land masses. The following regional identifiers are used: 1) USA = United States of America; 2) CAN = Canada; 3) OECD-E = OECD-Europe; 4) OECD-P = OECD-Pacific; 5) EEU = Eastern Europe; 6) FSU = Former Soviet Union; 7) CHINA$^+$ = China plus centrally planned neighboring countries; 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.

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.

While the AEEI parameter is used to examine demand-side impacts, imposition of carbon taxes (C-TAX) at a linear rate ($/tonne/15 yr) starts in the year 2005 (first “future” after the first times 1975 and 1990) to exaime supply-side impacts. Within the context of the version of the ERB model used, these taxes increase the price of fossil-fuel-based energy sources (in proportion to the respective carbon coefficient, kgC/GJ), diminish demand for these energy sources, and diminish economic productivity according to the ERB algorithms [(e.g., $GNP \propto 1/(price)^{\alpha}$]. The carbon taxes *per se* are “removed” from the respective economies, and in this respect the related impact on primarily-energy demand [$\propto (GNP)^{\beta}$] and associated decrease in GHG emission are overestimated; inclusion of both endogenous impacts on AEEI and C-TAX economy coupling/feedback represent important areas of future work.

RESULTS

A range of long-term energy scenarios have been generated based on varying an ensemble of scenario attributes.[9] Nine of the key scenario attributes varied in the Ref.-9 study are summarize on Table I, along with respective ranges of variations. The Ref.-9 study adopted a point-of-departure “Basis Scenario” to which these attribute variations were referenced. The nuclear-energy part of that Basis Scenario invoked a once-through LWR operation, a uranium

Table I. Primary Variables Examined in Ref-9 Study[8,24]

Variable/Attribute	Basis-Case Values
Population growth	UN projections (Fig. 3)[(a)]
Work-force productivity (1/yr)	(0.017,0.025) → (0.009,0.022)[(a)]
AEEI parameter, ε_k(1/yr)	0.0100[(b)]
Carbon tax rate ($/tonneC/15yr)	0 [(c)]
Uranium resource category	CR, KR, or TR[(d)]
NE capital cost, UTC_{LWR}($/We)	2.4 (2095 asymptote)[(e)]
MOX core volume fraction, f'_{MOX}	0.0[(f)]
LMR introduction constraints	(g)
FSB introduction constraints	(h)

(a) 1975 → 2095, dependent on region; varied ± 17% relative to basis case.

(b) reduction in secondary energy required to provide given energy service, independent of region and time (except where noted); varied over range (0.0,0.015) 1/yr.

(c) starting from 2005, rate varied over the range (0,50) $/tonneC/15 yr.

(d) CR = Conventional Resources; KR = Known Resources; TR = Total Resources, per Ref.-33 categorizations; varied over full range; KR adopted as base-case category.

(e) varied over range (2.0,3.0) $/We.

(f) final achieved value, starting in 1995 and increased according to time constant T_{MOX}; independent of region; for T_{MOX} = 10 yr, varied over the range (0.0,0.3).

(g) primarily UTC_{LMR}/UTC_{LWR} = 1.5, KR uranium resources, and no carbon tax; for these base-case conditions, LMRs were too costly for introduction.

(h) primarily minimum conversion ratio allowed and the ratio of UTC_{LMR}/UTC_{LWR} = 1.5 for IFR/LMR fast spectrum burner; the ratio UTC_{LMR}/UTC_{LWR} was varied over the range (1.2,1.5).

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. 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.

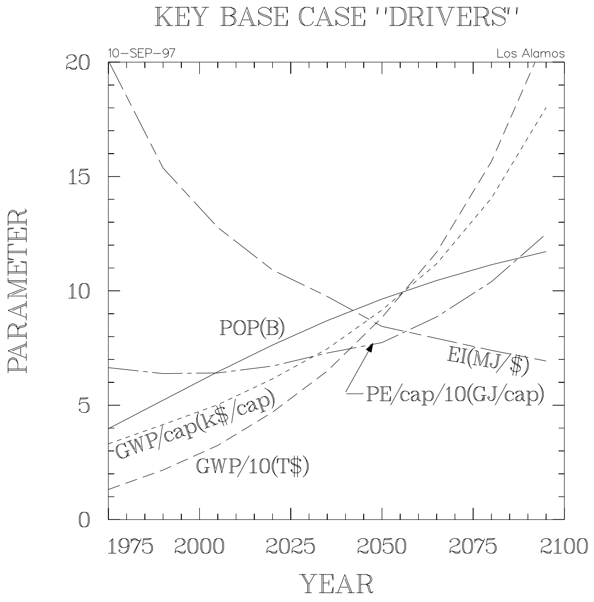

Figure 3. Key base-case aggregated drivers and related first responses: time dependencies of populations, POP (exogenous); GWP (price-adjusted basis case); GWP/POP (price-adjusted basis case); primary-energy intensity, EI = PE/GWP(endogenous), and *per-capita* primary energy, PE/POP(endogenous).

Basis Scenario

The Basis Scenario adopted for this study is largely that used in Ref. 9, but with plutonium recycle in f_{MOX_f} = 0.3 of the LWR reactor core volume. Figures 3-9 describe the essential elements of this MOX/LWR Basis Scenario. As for a majority of results presented herein, these results are an aggregate of the 13 global regions described by ERB. 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/$) = PE/GWP. Population growth is exogenously inputed from U.N. projections, whereas the exogenous base GWP input is modified to reflect changes in the prices of fossil fuels. The dependence of EI results from endogenous shifts in PE and (to a lesser extent) GWP. The evolving mix of primary energy demand for the Basis Scenario is given on Fig. 4; the diminishing market shares for oil and gas, and the increasing market share for solids (mainly coal, and some biomass) reflect the resource structure (*e.g.*, amount at a given grade and cost) used in the ERB model.[5,17] A moderately disaggregated view of primary- and nuclear-energy demand is depicted in Figs. 5 and 6, respectively. In terms of primary energy, the developing regions (DEV) become comparable users to OECD countries by ~2025, with a similar condition being reached for nuclear energy by 2050. The strong growth in primary- and nuclear-energy growth for the developing countries after ~2050 is driven largely by the CHINA$^+$ region, as is explicitly shown for nuclear energy in Fig. 6B.

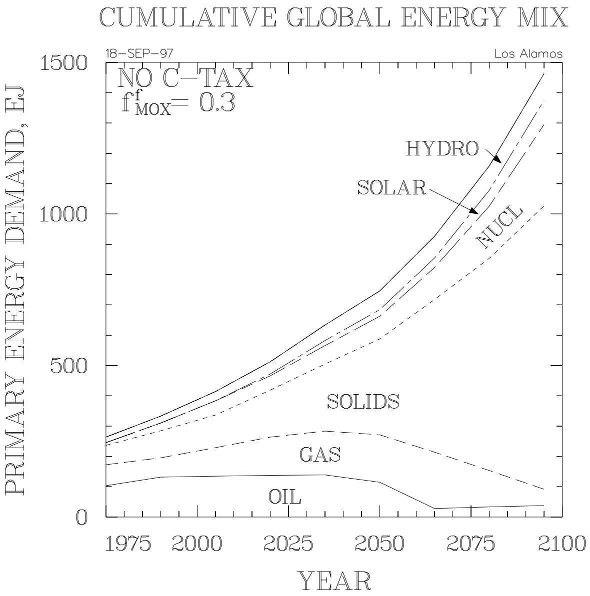

Figure 4. Cumulative evolution of global primary energy mix for the Basis Scenario (solids = coal + biomass): Cumulative primary energy.

The rate of CO_2 emission, R_{CO_2}(GtonneC / yr), for this no-carbon-tax Basis Scenario is shown on Fig. 7. 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. 7. 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 (2.13 GtonneC/ppmv). 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. 7. Carbon dioxide emissions from each of the 13 regions tracked by the ERB model is shown in Fig. 8; the CHINA$^+$ region becomes the dominant contributor of GHGs by the year 2025 for this Basis Scenario.

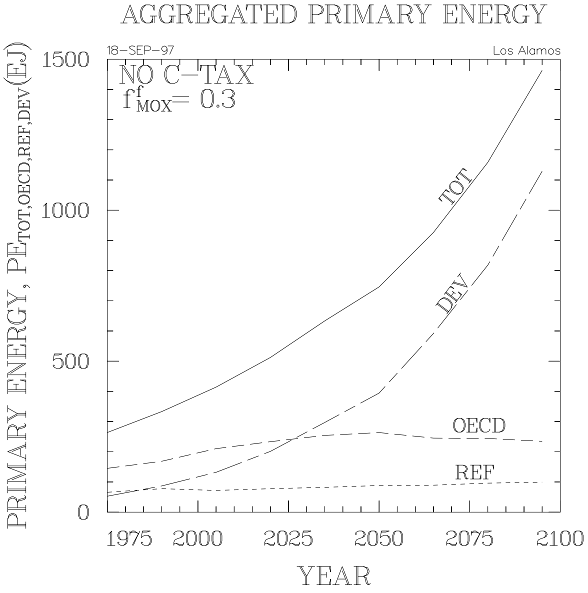

Figure 5. Evolution of aggregated total primary energy for Basis Scenario: OECD = US + CAN + OECD–E + OECD-P; REF + FSU + EEU; and DEV = CHINA$^+$ + ME + NAFR + SAFR + LA + IND + SEA.

The evolution of plutonium inventories by region is 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 adopted as the primary non-economic "cost" for nuclear energy against which any benefit of reduced GHG emission is measured. The PRI is a time-discounted sum of regionally weighted utilities evaluated from the viewpoint of a proliferator, which in turn is a weighted average of subutility functions that in turn reflect proliferator-oriented attributes that measure cost, technological difficulty, detection risk, and material availability;[10] the PRI indicates a value-based potential for proliferation rather than a probability for proliferation, is measured on a scale from zero to unity, and is subjectively evaluated from the perspective of a given region (*e.g.*, the U.S.).

The buildup of global plutonium inventories correlates with the relative CO_2 (carbon) accumulation, W/W_{IRV}, or the average global temperature rise, $\Delta T(K)$, that results. The latter is computed from the year t_{IRV}. These correlations are central to subsequent correlations of global climate change (GCC), nuclear-proliferation, and economic impacts. Specifically, 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 terms of a reduced "operating curve" for the Basis Scenario on Fig. 9. 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. 9. 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 9 also compares the PRI impacts (for the no-carbon-tax case) of plutonium recycle (f_{MOX_f} = 0.30) and the use of the once-through (LWR) fuel cycle. Plutonium recycle increases the PRI by ~10% while having little impact on reducing GCC impacts (*e.g.*, ΔT). Actually, the lines of constant time (an isochrone for 2095 is shown on Fig. 9) are almost vertical, with a slight

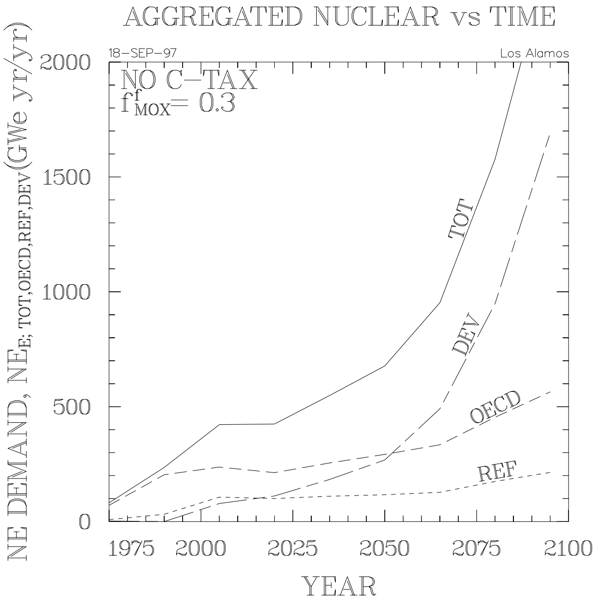

Figure 6A. Aggregated and (13) regional nuclear energy demand for the Basis Scenario: Aggregated total and macro-regional nuclear energy demand.

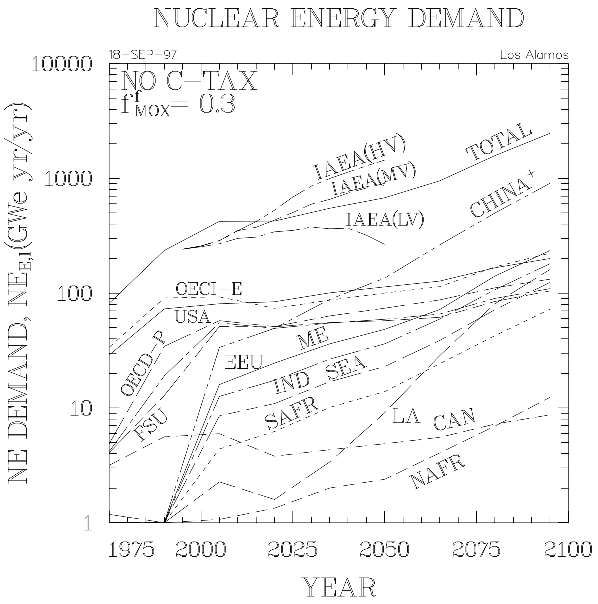

Figure 6B. Aggregated and (13) regional nuclear energy demand for the Basis Scenario: Regional nuclear energy demand.

off-vertical orientation indicating that the small added cost associated with the f_{MOX_f} = 0.0 → 0.3 transition, which increases the cost of nuclear energy slightly and reduces (slightly) demand, results in a small increase in fossil-fuel use, and leads to somewhat larger values of ΔT (< 0.05 K) for the f_{MOX_f} = 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, however, the impact of variations in the demand-side parameter AEEI are first reported.

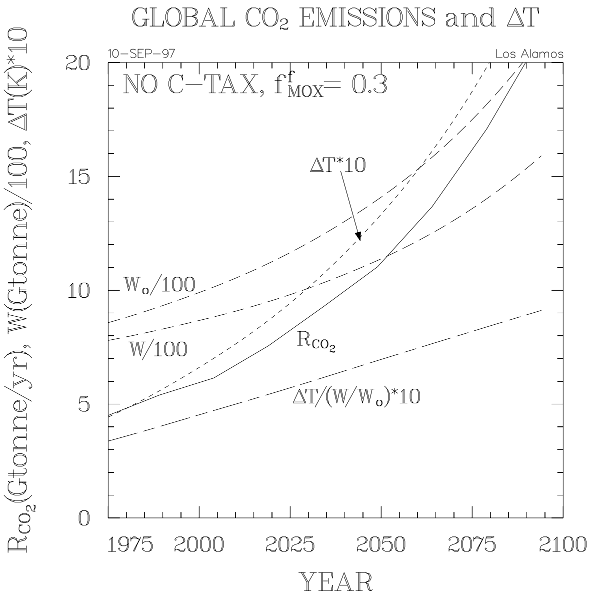

Figure 7. Time dependence of total CO_2 (carbon) emission, integrated emissions, atmospheric accumulation of emissions, and corresponding global average temperature rise, as determined from the linear integral-response model;[15,16] results applied to the zero carbon-tax basis case.[24]

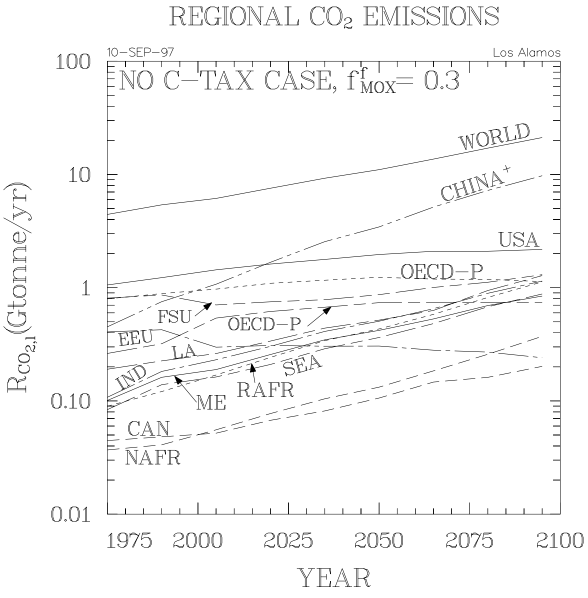

Figure 8. Atmospheric carbon emission rates as a function of time and region for Basis Scenario.

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 Basic Scenario, 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.

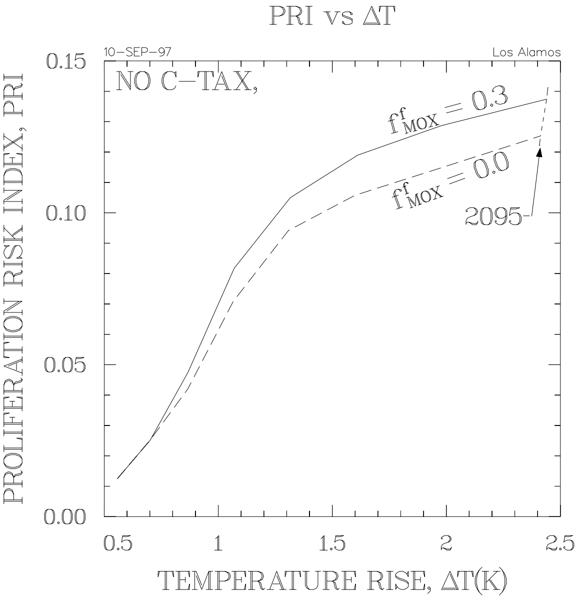

Figure 9. Correlation of proliferation-risk index with average global temperature rise for case without carbon tax imposed; a comparison of PRI impacts of plutonium recycle (*e.g.*, f_{MOX_f} = 0.0 *versus* 0.30) is shown.

The scenarios considered under "AEEI variations" (Table I) 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 down from 0.015 (in 1990) to 0.0 in 2095. These impacts are summarized on Figs. 10-13. Specifically, the impact on primary- and nuclear-energy demand is depicted on Figs. 10 and 11. The reflection of these changes in end-use efficiency on the energy intensity (again, starting in 1990) indicates that 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. 10), but relatedly leads to wide swings in carbon-dioxide emissions, as is shown on Fig. 12. The average global temperature rises that result are depicted on Fig. 13. 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 mitigating 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.

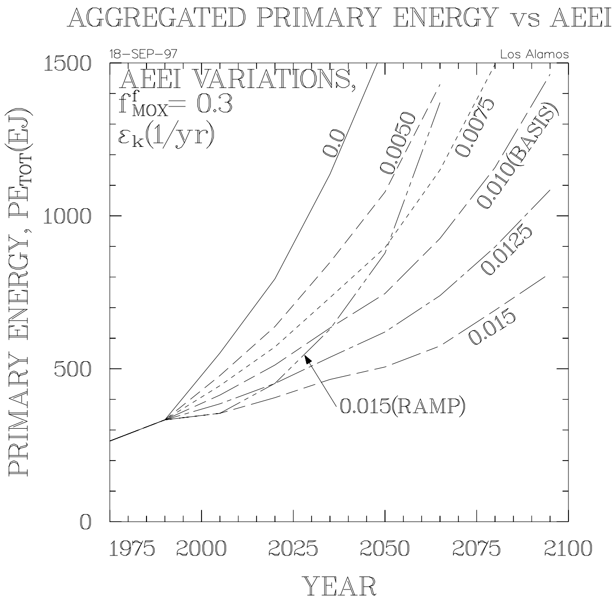

Figure 10. Primary energy demand as a function of time and AEEI; the ε_k = 0.015(RAMP) case starts ramping from the indicated value in 2005 and linearly decreases to zero by 2095.

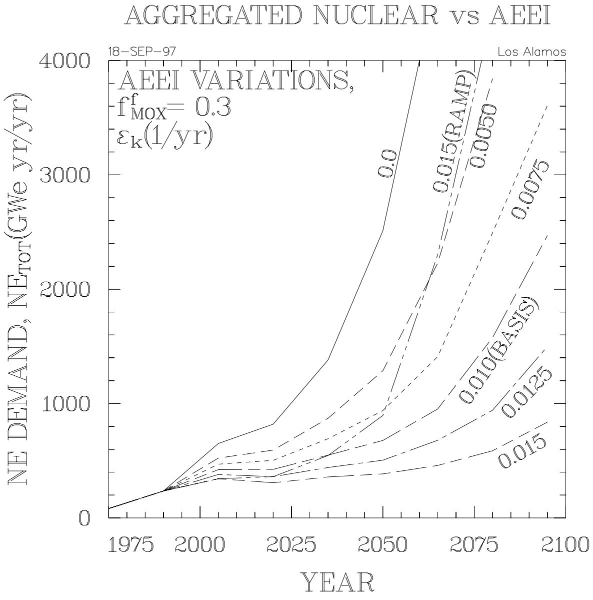

Figure 11. Nuclear energy demand as a function of time and AEEI; the ε_k = 0.015(RAMP) case starts ramping from the indicated value in 2005 and linearly decreases to zero by 2095.

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.

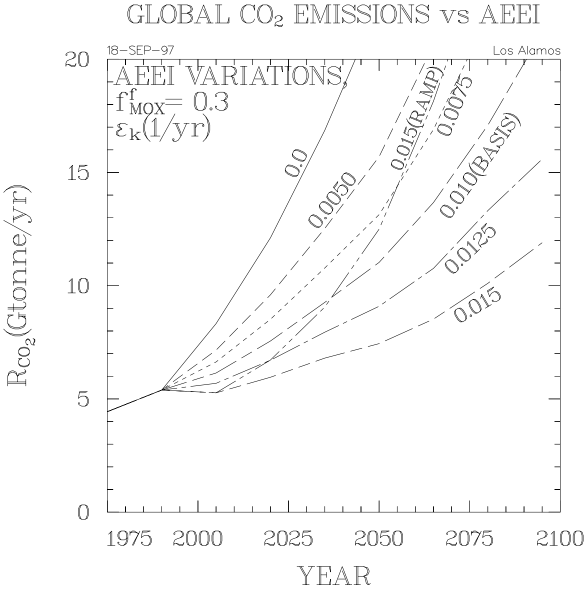

Figure 12. Carbon-dioxide (carbon) emission rate as a function of time and AEEI; the ε_k = 0.015(RAMP) case starts ramping from the indicated value in 2005 and linearly decreases to zero by 2095.

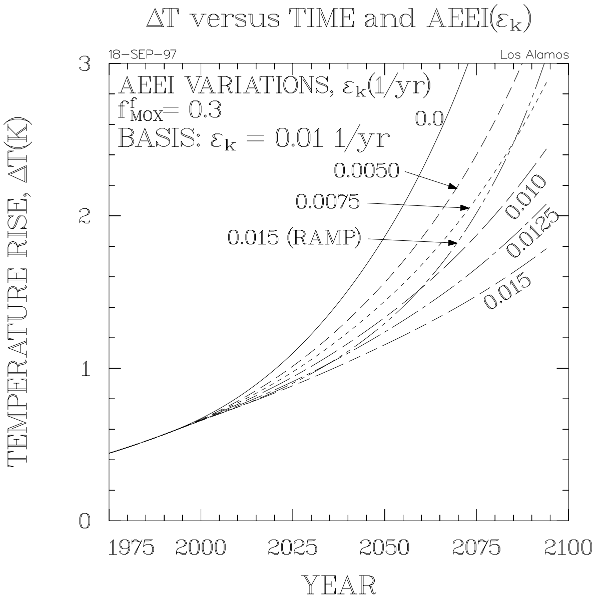

Figure 13. Average global temperature rise as a function of time and AEEI; the ε_k = 0.015(RAMP) case starts ramping from the indicated value in 2005 and linearly decreases to zero by 2095.

Supply-side Impacts: Carbon Taxes

Energy Demand and Mix. 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 ranging from 0 to 50 \$/tonneC/15yr; hence, for a rate of 40 \$/tonneC/15yr, the carbon tax at the last time considered (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. 14; 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 as follows; coal looses the greatest market share (~65% → 22% in 2095), nuclear and solar (electric) energies show a strong increase in market share (~19% → 46% and ~5-6% → 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; the fraction of primary energy that is used to generate electricity increases from ~16% to 22% in 2095 for the maximum carbon tax rate.

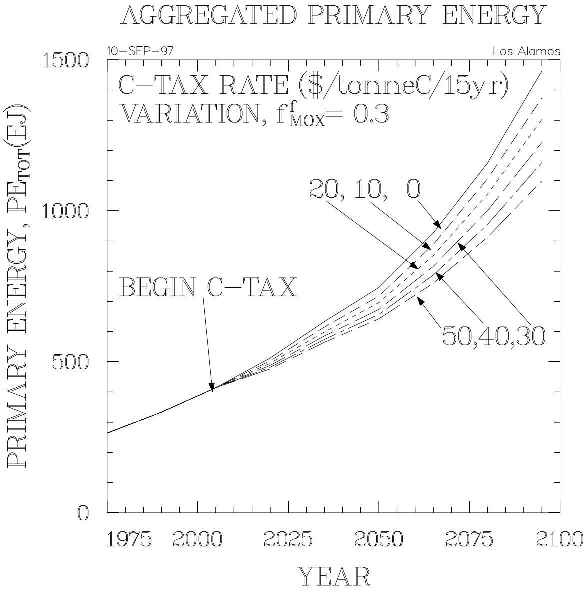

Figure 14. Primary energy demand as a function of time and carbon tax rate, starting in 2005.

Focusing on nuclear energy, Fig. 15 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 ~75 GWe/yr to ~85 GWe/yr (for an 80% plant availability factor). Similar deployment rates are required in the out years for the no-carbon-tax case. Figure 16 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 most agressive carbon tax rate considered.

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. 17, 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.

Figure 18 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 anthroprogenically driven global warming ($W_{IRV} = 594$ GtonneC, $\Delta T = 0$), the CO_2 emission rates given on Fig. 17 are used to estimate atmospheric carbon accumulations and related global temperature rises, ΔT(K). Figure 19 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).

E^3-Trilemma Trade Offs. 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 the need to reduce risks related to nuclear-weapons 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 a discussion of some aspects of adverse economic impacts of imposing unallocated carbon taxes.

Proliferation versus GCC Risks. At the level of this analysis, the culmination of the comparative risk assessment is the PRI *versus* ΔT relationship (Fig. 9) 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. 20 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. 20 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.

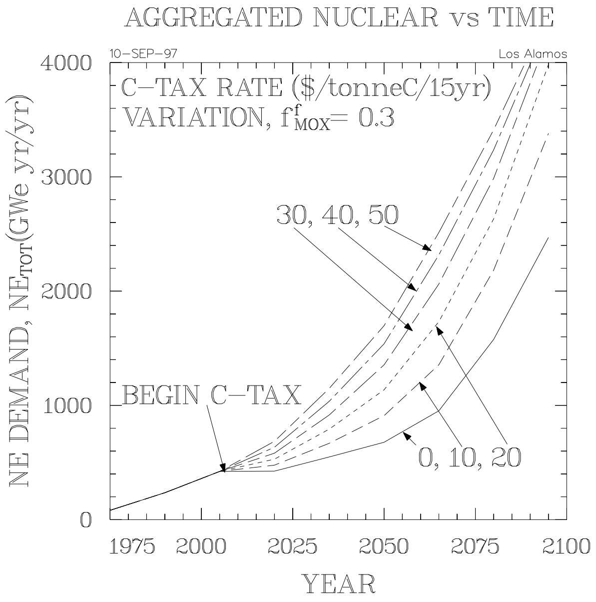

Figure 15. Nuclear energy demand as a function of time and carbon tax rate, starting in 2005.

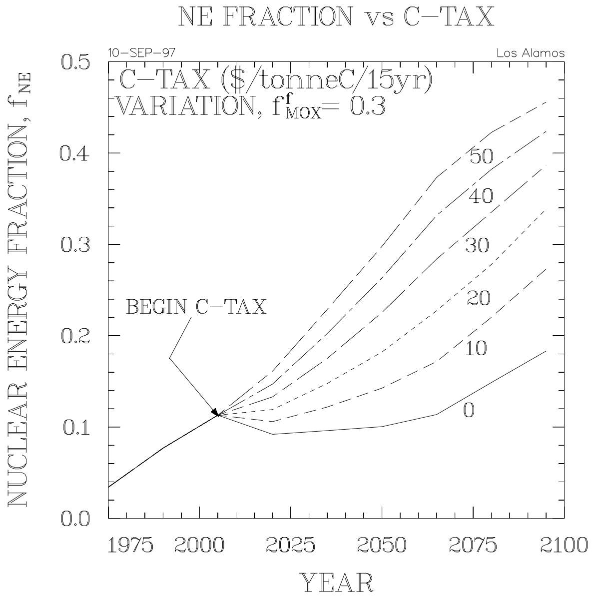

Figure 16. Nuclear energy as a fraction of total primary energy as a function of time and carbon tax rate, starting in 2005.

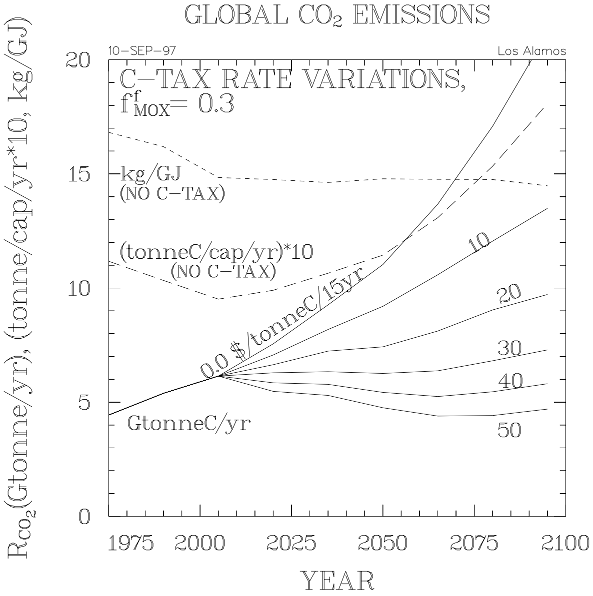

Figure 17. Atmospheric carbon emission rates as a function of time and carbon tax rate, beginning in 2005; emission rates along with *per-capita* and per-primary-energy emissions for zero carbon taxes are shown.

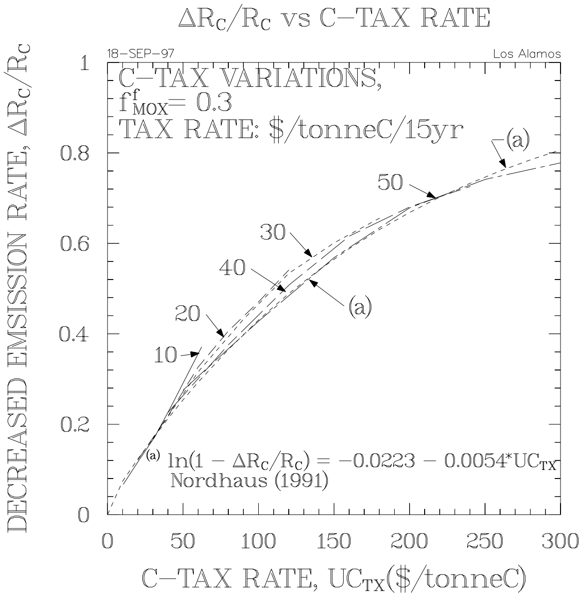

Figure 18. Decrease in atmospheric carbon emission rate as a function of carbon tax for a range of carbon tax rates; a regression fit to a number of model predictions[38] is also shown.

Economic versus GCC Risks. 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 sometimes 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, $\Delta R_{CO_2} = R_{CO_2}$ (No C-TAX) – R_{CO_2} (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 21 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. 22 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 23 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 value 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. 22 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. 23. 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.

Composite Demand-Side/Supply-Side Impacts

The relative impacts on stemming greenhouse warming through demand-side (increased AEEI, $\varepsilon_k = 0.0100 \rightarrow 0.0150$ 1/yr), supply-side (carbon tax rates, 0 → 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 II are compared. Figures 24 and 25 give the time dependence of primary-energy and nuclear-energy demand, respectively, for these four case. 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. 26. 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. 22), however, can amount to ~33% reductions for the case of UC_A based only on TAX. 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. 27; 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]

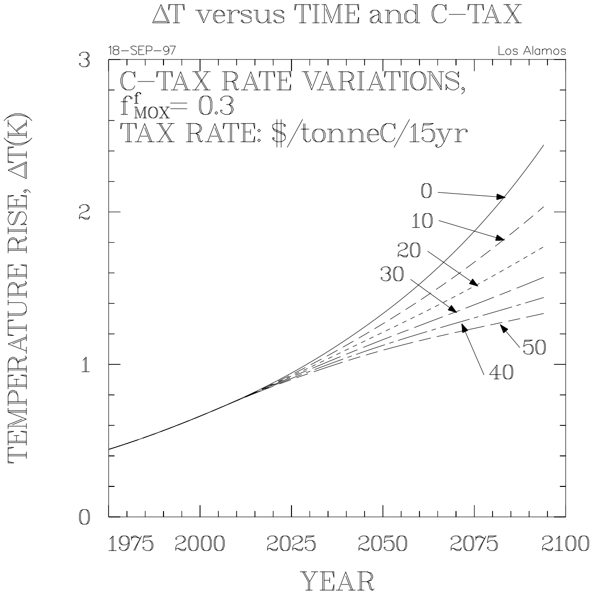

Figure 19. Time dependence of average global temperature rise for a range of carbon tax rates, starting in 2005.

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 moderate impacts on greenhouse warming *per se* (Table II), when used in conjunction with carbon taxes, important decreases in (the highly approximate) measures of unit abatement costs, UC_A result. Similar symbiotic effects may also come into play through attempts to mitigate proliferation risks along with GCC risks (Fig. 27).

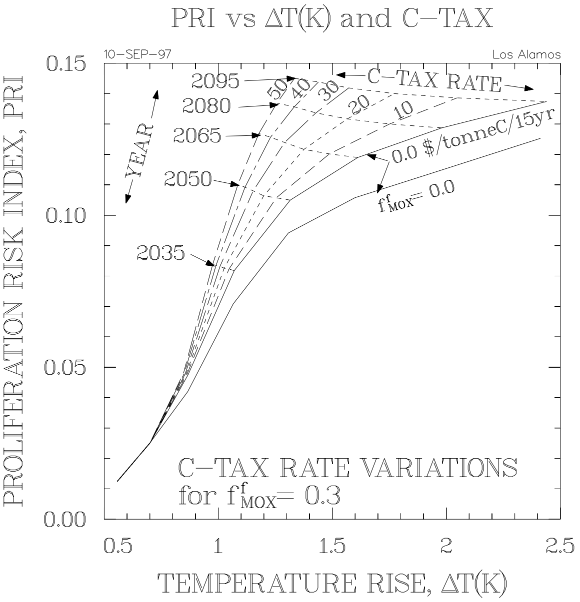

Figure 20A. Direct comparison of proliferation-risk-index *versus* atmospheric temperature-rise "operating curves" as the rate of carbon taxation is varied: direct comparison of PRI *versus* ΔT, showing isochrones.

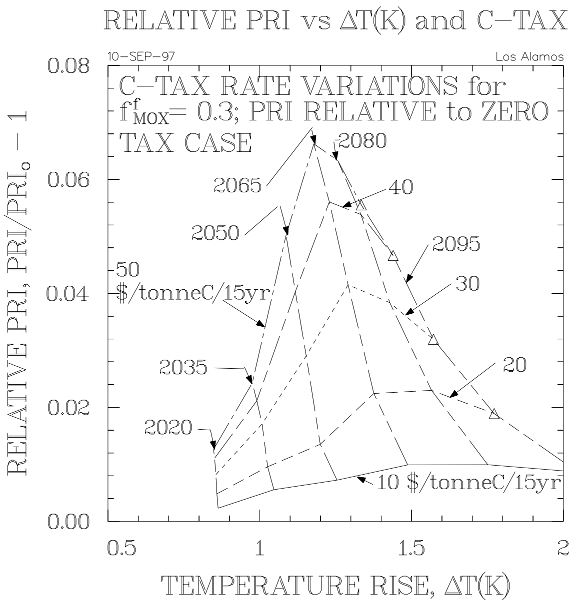

Figure 20B. Direct comparison of proliferation-risk-index *versus* atmospheric temperature-rise "operating curves" as the rate of carbon taxation is varied: change in PRI relative to the no-carbon-tax case, showing isochrones.

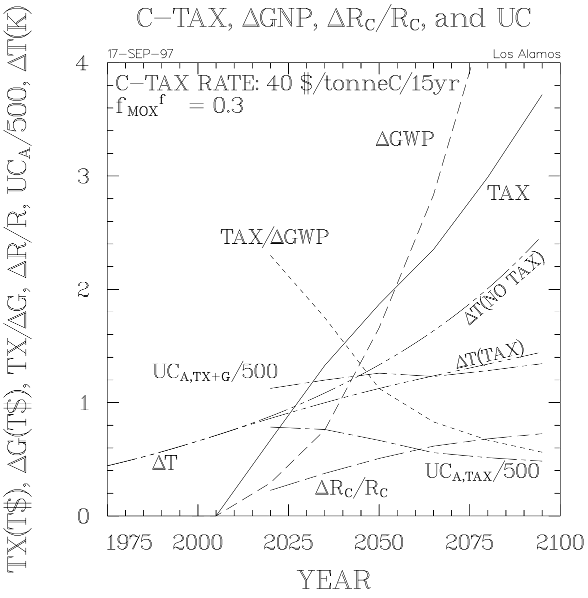

Figure 21. Time dependence of total carbon taxes, decreased GWP, tax-to-GWP ratio, percent decrease in atmospheric carbon emission rate, unit cost of CO_2 abatement, and average global temperature rise for a carbon tax rate of 40 $/tonneC/15yr.

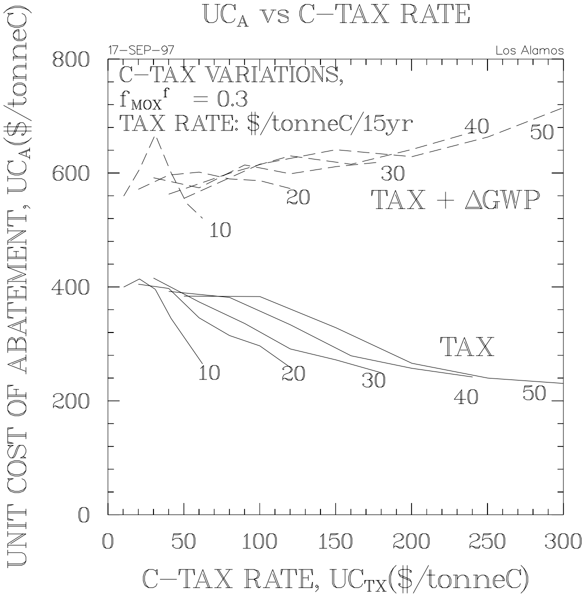

Figure 22. Dependencies of two measures of unit cost of abatement, UC_A($/tonneC), as a function of unit carbon tax, UC_{TX}($/tonneC), for a range of carbon tax rates ($/tonneC/15yr).

A central theme of this study is embodied in 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 (*e.g.*, PRI, ΔT, UC_A, *etc.*) and are far from being comprehensive, this investigation represents a beginning. 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. 20 and 21). 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. 20) 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/100yr 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.

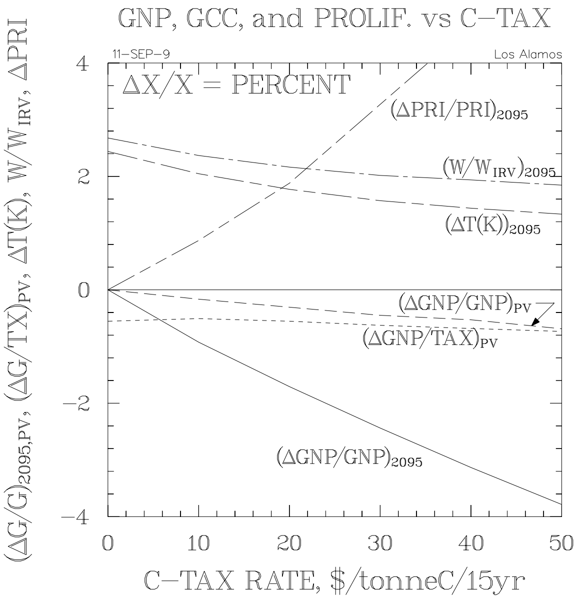

Figure 23. Impact of carbon tax rates on either present value (PV) or last-year (2095) gross productivity (G = GWP), comparing GCC parameters (W/W_{IRV} and ΔT) with proliferation parameters (PRI); all relative changes ΔX/X are expressed as percentages: direct dependence on carbon tax rate.

Table II. Summary of Cases Used to Compare Demand-Side *versus* Supply-Side Approaches to Mitigating Greenhouse Warming

Scenario Identification	Carbon Tax Rate ($/tonneC/15yr)	AEEI ε_k (1/yr)	Percentage Changes in 2095 Values				
			PE	NE	EI	R_{CO_2}	ΔT
Basis	0	0.0100	--	--	--	--	--
Carbon Tax	40	0.0100	–20.	+83.	~0.	–73.	–41.
AEEI	0	0.0125	–25.	–39.	–29.	–29.	–5.
AEEI + C-TAX	40	0.0125	–43.	+22.	–39.	–83.	–45.

AEEI autonomous energy efficiency improvement
ε_k = annual rate of increase of SE → ES conversion efficiency
SE = secondary energy
ES = energy service
PE = primary energy
NE = nuclear energy
EI = primary energy intensity, PE/GWP(MJ/$)
R_{CO_2} (GtonneC/yr) = CO_2 emission rate
ΔT (K) = average global surface temperature rise

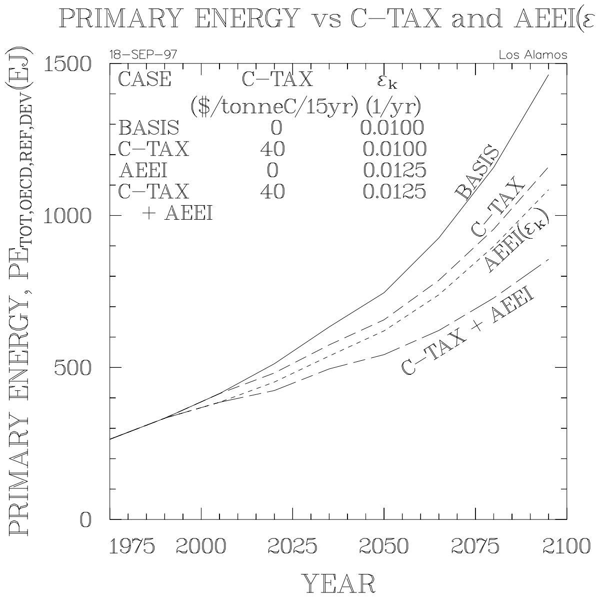

Figure 24. Primary energy demand as a function of time for a combination carbon tax rate and AEEI, showing relative impacts of supply-side (carbon tax) and demand-side (AEEI) scenario attributes.

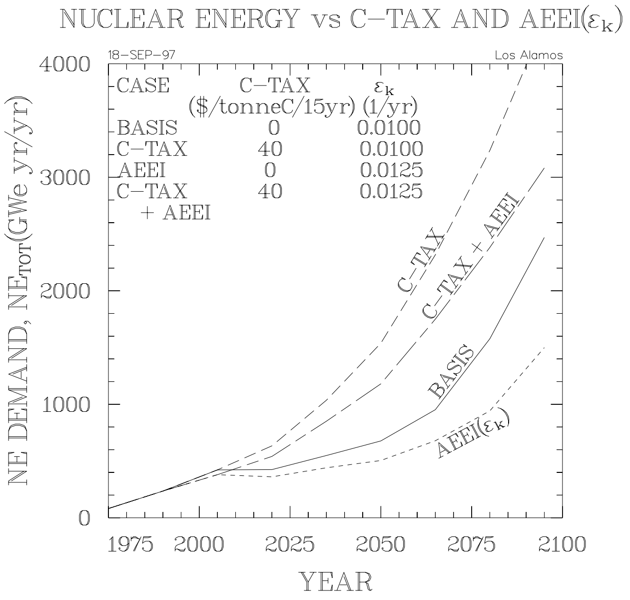

Figure 25. Nuclear energy demand as a function of time for a combination carbon tax rate and AEEI, showing relative impacts of supply-side (carbon tax) and demand-side (AEEI) scenario attributes.

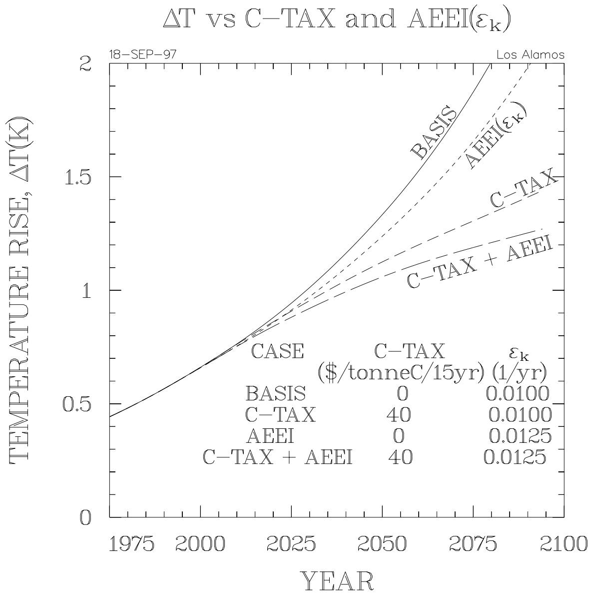

Figure 26. Average global temperature rise as a function of time for a combination carbon tax rate and AEEI, showing relative impacts of supply-side (carbon tax) and demand-side (AEEI) scenario attributes.

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. 28, this 25% increase in (global) AEEI reduces the amount of nuclear energy required for a ~90% reduction in global warming (in 2095) by ~30%.

Throughout the narrative, 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 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 have been shown to be important[17] and must be developed further.

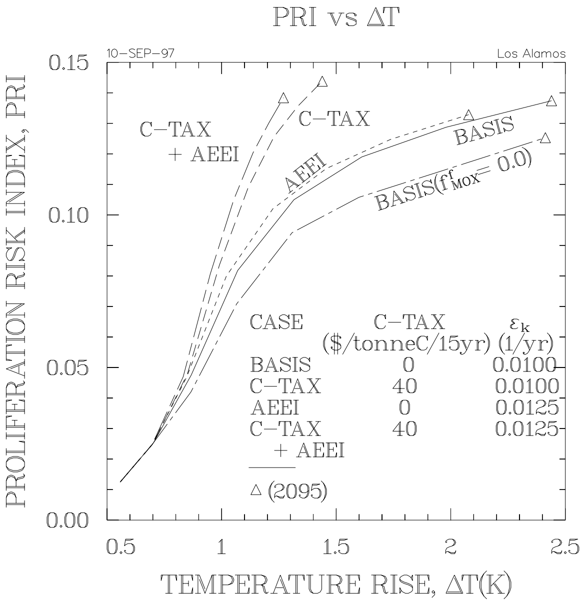

Figure 27. Direct comparison of proliferation-risk-index *versus* atmospheric temperature-rise "operating curves" for a combination carbon tax rate and AEEI, showing relative impacts of supply-side (carbon tax) and demand-side (AEEI) scenario attributes.

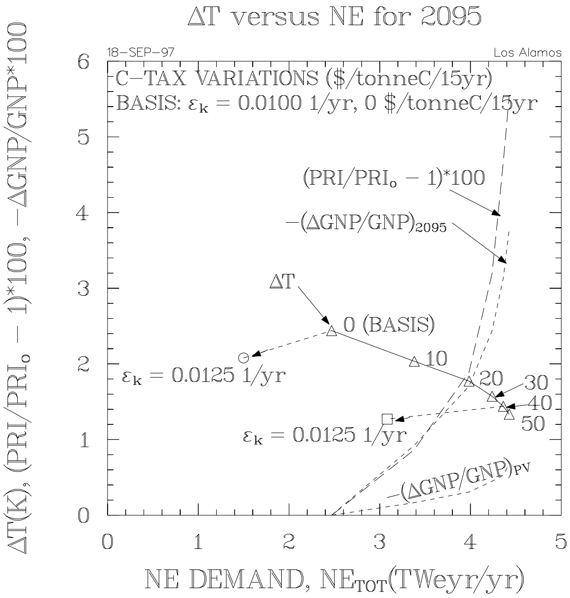

Figure 28. Dependence of global temperature rise on carbon-tax-induced (supply-side) nuclear-energy demand, showing impact of demand-side increases in AEEI for the Basis Scenario (no carbon taxes) and for a case where the carbon tax is imposed at a rate of 40 $/tonneC/15yr; also shown is the increase in PRI relative to the Basis Scenario as well as the relative decrease in GNP.

- *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 the range of forms (*e.g.*, reactor, spent-fuel, separated, *etc*., plutonium) 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) expands 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
ATW	Accelerator Transmutation of Waste
BAU	business as usual
C-TAX	carbon tax
CAN	Canada
CHINA$^+$	China plus neighboring centrally planned countries
CIS	Commonwealth of Independent States (FSU)
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)
DR(1/yr)	discount rate (for proliferation risk discounting,[11,12,10] or for estimating present worths of GWP or carbon taxes[38])
E^3	economics/energy/environmental
EEU	Eastern Europe
EI(GJ/$)	energy intensity, ratio of primary or final energy to GNP
ERB	Edmonds, Reilly, Barns model[5]
ES	energy services (residential/commercial, transportation, industrial)
FC	nuclear fuel cycle
FF	nuclear 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
G(B$/yr)	gross world product, also GWP
GCC	global climate change
GDP($/yr)	gross domestic product
GHG	greenhouse gas
GNP($/yr)	gross national product
GWP($/yr)	gross world product
HV	high (nuclear energy growth) variant
HYDRO	hydroelectric
IAEA	International Atomic Energy Agency
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
LMR	liquid metal reactor
LV	low (nuclear energy growth) variant
LWR	light water reactor
KR	known uranium resources
LWR	light water reactor
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
NAFR	Northern Africa
NE	nuclear energy
NM	nuclear materials
NT	no carbon taxes
NUCL	nuclear
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
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
PV	present value computed using discount rate DR
ppmv	volume parts per million (2.13 GtonneC/ppmv)
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 $\dot{M}_{CO_2}$
REA	reactor plutonium
REC	fully recycle (N recycles to LWRs) plutonium
REF	(economically) reforming countries (EEU + FSU); also, reference time (1975)
RP	reprocessing
RPU	reactor plutonium
RS	repository
SAFR	Southern Africa
SE	secondary energy (liquids, gases, solids, electricity)
SE/PE	PE → SE conversion efficiency
SEA	South and East Asia
SEP	separated plutonium
SF	spent fuel
SFT	total spent fuel
SPU	separated plutonium (RP + FF)
TAX	carbon tax case designator
TH	thermal → electric conversion
TOT	total, world
TR	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) → ES(k) transformation efficiencies
η_{TH}	thermal-electric conversion efficiency