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Nuclear's Role in 21st Century Pacific Rim Energy Use: Results and Methods

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NUCLEAR'S ROLE IN 21ST CENTURY PACIFIC RIM ENERGY USE: RESULTS AND METHODS

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Extrapolations contrast the future of nuclear energy use in Japan and the Republic of Korea (ROK) to that of the Association of Southeast Asian Nations (ASEAN). Japan can expect a gradual rise in the nuclear fraction of a nearly constant total energy use rate as the use of fossil fuels declines. ROK nuclear energy rises gradually with total energy use. ASEAN's total nuclear energy use rate can rapidly approach that of the ROK if Indonesia and Vietnam make their current nuclear energy targets by 2020, but experience elsewhere suggests that nuclear energy growth may be slower than planned. Extrapolations are based on econometric calibration to a utility optimization model of the impact of growth of population, gross domestic product, total energy use, and cumulative fossil carbon use. Fractions of total energy use from fluid fossil fuels, coal, water-driven electrical power production, nuclear energy, and wind and solar electric energy sources are fit to market fractions data. Where historical data is insufficient for extrapolation, plans for non-fossil energy are used as a guide. Extrapolations suggest much more U.S. nuclear energy and spent nuclear fuel generation than for the ROK and ASEAN until beyond the first half of the twenty-first century.

I. INTRODUCTION

Most of the ASEAN region is experiencing rapid economic growth, as successively did Japan and South Korea upon their recoveries respectively from World War II and the Korean conflict. It is thus interesting to both compare and contrast the energy use implications of economic growth in these Pacific Rim markets. The ASEAN market is of particular interest for the proposed Global Nuclear Energy Partnership (GNEP). This is because the ASEAN region currently lacks an indigenous nuclear fuel cycle but will be seen here to have the potential to approach the level of nuclear energy use in South Korea over the next several decades. At present, in particular, none of the ASEAN nations have had to come to grips with the internally contentious question of where to permanently dispose of radioactive waste from commercial nuclear reactors. Moreover, by their universal accession to the Nuclear Nonproliferation Treaty and by internal arrangement through the Bangok Treaty, the ASEAN nations have foresworn nuclear explosives production and constitute a nuclear weapons free zone. Should this understanding within ASEAN stand the test of time, then it could be particularly attractive for ASEAN nations to export spent nuclear fuel and avoid both the uneven buildup of nuclear weapons potential within the region and the problem of disposing of large amounts of radioactive material.

The small ratio of twenty-first century spent nuclear fuel production in ASEAN versus the countries that already have nuclear fuel cycles is quantified here. This illustrates why taking back spent nuclear fuel from ASEAN countries should have little impact on acceptor nuclear fuel cycle facilities. Such an arrangement will require that the spent fuel acceptors themselves have an adequately well functioning nuclear fuel management process, which for the most likely acceptor countries will probably take some time to fully establish. Thus it is important not only where ASEAN nuclear energy use is headed in the longer term, but also when it may start and how it would be phased in.

II. QUANTITATIVE ESTIMATES

The extrapolation methods used here are based on systematic calibration against historical data within a well defined analytic framework. This approach avoids results that either fail to fit available empirical data or to sensibly extrapolate into the distant future. We have chosen here an analytic and computational approach that allows extrapolation to a sustainable equilibrium into the very distant future, including the possibility of spent nuclear fuel reprocessing and recovery of uranium from low grade ores and as a byproduct of other materials extraction, possibly even from seawater. One motivation for this approach is that thinking about driving nuclear fuel cycles to near completion requires examination of very long time scales. For example, current U.S. plans call for delaying sealing of an underground repository for about three hundred years, and for producing a fleet of reactors that would likely take most of the rest of this century to phase in and then continue on for multiple rounds of actinide burning to minimize the end-level actinide content. While here we only graph global and Pacific rim nuclear energy use into the second half of this century, the underlying calculations and terminal boundary conditions used are consistent with a self-consistent role for nuclear energy in the long-term transition to an energy production system with fossil fuel use tending asymptotically to zero. A brief outline of the methods is given in the Appendix, and more detail can be found in a more extensive report (Rethinaraj 2005).

The approach used here relies on a complete set of data from 220 UN reporting units back through 1950, supplemented with earlier country-level estimates of the use of fossil fuel and hydroelectric power. For the present study, Japan, the ROK, and the USA were examined at the country level, and the data for the ASEAN countries were added together. Other countries were separated into a "tropical" (and subtropical) set of mostly developing countries lying wholly between forty degress north and south latitude, with the rest of the world lumped into an aggregate "temperate" region. Here the words "tropical" is in quotes as a reminder that some subtropical and not all of the tropical countries are included here in what is referred to below as simply the tropical region. Likewise, the United States and Japan are treated separately and not included here in what is referred to as the temperate region. All of the regions and countries are coupled through the modest impact of depletion of more readily extractable global uranium resources on the cost and thus the market fraction of nuclear energy. However, over the time period for which results are shown in this report, the impact of global uranium resource depletion on nuclear energy production costs is small enough that it has almost no effect on the results.

II.A. Population and GDP

This paper presents extrapolations beyond the middle of this century. The reason for using such a distant horizon is to look beyond the initial likely adoption of nuclear electric power production in one or two ASEAN countries around 2020 to see how nuclear energy use might subsequently grow in the region. Figures 1 gives some insight into both the possibility and hazards of making such long term extrapolations. This figure plots on a logarithmic scale the per capita GDP for the United States, Japan, ROK, and the tropical region. The quantities plotted in Figure 1 are per capita GDP in terms of U.S. dollars worth of purchasing power parity at 1990 prices. The purchasing power parity (PPP) approach corrects international exchange rates to account for the different cost of goods and services in local as apposed to international markets. Figure 1 shows a rapid recovery by Japan after World War II, followed by a period of exponential growth in per capita GDP paralleling that of the United States and then a slowing starting in the 1990s. The rest of temperate region includes China lumped with it as not of special interest in this present study. This temperate region exhibits an intermediate level of per capita GDP between that of lower latitude countries and that of the ROK, Japan, and the United States.

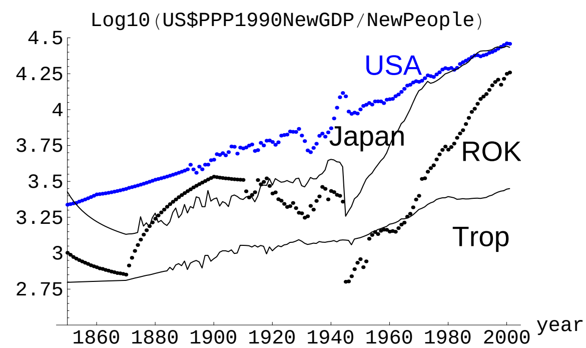

Fig. 1. Base ten logarithm of the ratio of the increment of GDP over its year 1820 base value to increment of population over its base value, with monetary units and region labels as in Figure 1.

The possibility of making fairly long term extrapolations is supported by the persistent long term trends observable in Figure 1, but this information also suggests caution in assuming that these trends will never be interupted by dramatic departures. The method to be used here calibrates extrapolations only against data from periods devoid of these dramatic departures, for analytic simplicity using an intitial condition that extrapolates backward in time along a nearly linear path on the plots in Figure 1 and and neglecting the early perturbations from this path. This method gives sensible extrapolations as long as similarly dramatic events do not occur in the future. High fatality epidemics, large scale conflicts, serious economic instability, or enormous natural disasters may have a low probability of producing dramatic perturbations in any particular country or region, but it should be kept in mind that such an event may well again affect one or more countries or regions somewhere on the globe sometime this century. No attempt has been made here to model the impact of such disasters, so the extrapolations shown here should be seen as reasonable estimates that may be approximately realized if in fact no such large scale disruptions occur in the countries or regions of interest.

II.B. Analysis Methods

The decrease in carbon intensity of energy production with cumulative fossil carbon use is an important consideration when projecting nuclear energy futures. Here piecewise linear fits to the historical decrease in carbon intensity of energy production with cumulative fossil carbon use are extrapolated down until natural gas becomes the largest form of fossil energy use. The linear assumption is consistent with fits to estimates by H-H. Rogner (1997) of fossil fuel endowment as a fraction of extraction costs at a given technology level. After the carbon intensity of energy use reaches just over half of the value for pure coal, as in a natural-gas-dominated economy with smaller contributions each from more and less carbon-intensive energy sources, the magnitude of the slope of the decline is reduced by half. This continues until cumulative global carbon emissions are sufficient to raise global average temperatures by about two degrees Celcius over their preindustrial base value, based on data-calibrated extrapolations using a simple atmospheric carbon and heat balance model described by Petschel-Held et al. (1999). After this the historical observed linear decline of carbon intensity of energy with cumulative carbon use resumes, leading asymptotically to a sustainable fossil-free equilibrium. This final phase, which implicitly assumes an effective and essentially global effort on limiting carbon emissions, lies near the end of this century and well beyond the time range for graphs in the present paper. However, this assumption does very slightly affect the results shown because it is incorporated into the terminal boundary conditions for optimizing the evolution over time of capital and labor applied to energy production and gross domestic product (GDP). The expected values for the probability distributions used for extrapolating carbon intensity of energy production given in Singer et al. (2007) illustrate in more detail the type of approach used here.

Several features of the present approach allow overall energy use to be calibrated against available data and sensibility extrapolate to a sustainable limit in the long term. First and most important is the elaboration of a sufficiently comprehensive database and automatic procedure for aggregating it into any desired groupings of countries. Second is accounting for all clearly statistically significant periodic deviations of energy use (and population and GDP growth rates) around background trends. When combined with a long enough time series of data used, this avoids the large differences between successively published extrapolation results that have often been obtained by essentially using just the current values and linear or exponential fits to recent trend lines.

A third feature of this analysis is the use of population growth rates to calibrate an index of development that evolves pre-industrially from 0 to a future sustainable limit of 1 on a logistic curve, latter portions of which are illustrated below in Figure 2. This reflects the commonplace observation that high population growth rates tend to correlate with low levels of economic development and productivity, and vice versa. Data on GDP growth rates are then used to calibrate the quantitative dependence of productivity on this development index. The development index is raised to a power estimated from GDP growth rates and indicates how far along on its economic development pathway a country or region is, not its absolute per capita GDP. The lower current value of the development index for the United States than three other cases shown in Figure 3 is a reflection of higher current population growth rates and the possibility of future growth in U.S. per capita GDP, not specifically of the United States' current relative standing in per capita GDP. In the calculation method used, this finite-range development index is actually used instead of the infinite range of time as an independent variable. This avoids a difficulty that methods with finite time horizon have with using a long-term approach to sustainability as a terminal boundary condition.

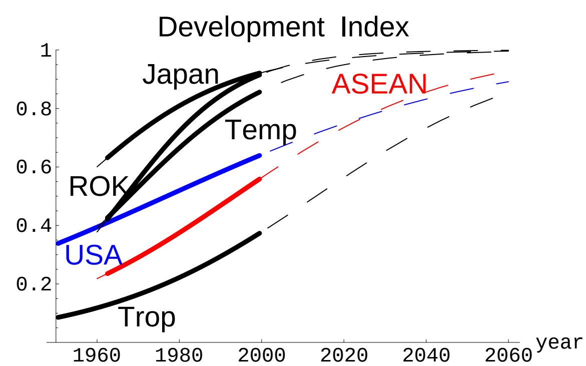

Fig. 2. The development index shown here as a function of Julian year is the increment of population over its year 1820 base level divided by the long term limit of this increment. $a = 1/(1 + \mathrm{Exp}[-\bar{\nu}(\tilde{t} - \bar{t}_0)])$ is the formula for the logistic function plotted here for each region, where $\mathrm{Exp}[x] = e^x$ with $e \approx 2.71828$, $\bar{\nu}$ is initial growth rate, and $\bar{t}_0$ the value of time $\tilde{t}$ at half-maximum population increment. The solid portions of the curve indicate the temporal range of population data used for the calibration. From the bottom up in 1980 the curves are for the tropical region, ASEAN, USA, temperate region, Republic of Korea, and Japan respectively.

A fourth feature of the analysis approach is that all but one of the parameters used in this analysis are systematically data calibrated. The one parameter that instead requires a more approximate technology assessment relates to the above-mentioned dependence of energy sector productivity on fossil fuel depletion.

It is not that we are completely devoid of observational information on how much cheaper delivered energy is when inexpensive fossil fuels are available. The roughly two-fold variation in busbar electricity costs in the United States between regions with cheap fossil or hydroelectric resources and those that rely more heavily on nuclear or nearly competitive wind or solar thermal electric energy gives some indication, just not enough to systematically calibrate a probability distribution. Thus, a factor of two difference in energy sector productivity with and without inexpensive fossil fuels at a given level of technology development is assumed here.

Data calibration of the evolution of competition between different energy sources is done here on a pairwise basis. In each case the capture of market fraction by a newer energy source depends on its cumulative experiential learning. For fossil fuels and uranium the resource depletion that comes with cumulative use also provides a countervailing pressure against their utilization. Graphs of the results given below will help illuminate how these countervailing pressures influence the evolution of the fractions of total energy from different fuel sources.

III. EXTRAPOLATED ENERGY USE

The overall energy use trends and the periodic fluctuations around these are extrapolated out to 2060 in Figure 3. The calibration method assumes that the percentage deviation between data and fits follow lognormal statistical distributions, an assumption consistent with statistical tests (Wei 1990) on timeseries nearest neighbor correlations and periodic variations other than those used to fit the data. The rapidly varying curves shown in Figure 3 are just the maximum likelihood fits of this type and should not be interpreted as providing uniquely valid extrapolations of the data. The rest of this paper only uses the background trends illustrated by the smooth curves in Figure 3, which are less sensitive to sampling probability distributions for model parameters than the rapid variations around these trends. These background trends are shown for Japan, South Korea, and ASEAN with an expanded vertical scale in Figure 4. The units used in Figures 6 and 7 are exajoules per year (EJ/yr). Electrical energy is converted to thermal equivalent using a reference thirty-eight percent thermal to electrical energy conversion efficiency.

The ten-fold difference in the vertical scales on Figures 3 and 4 reflects the fact that the Pacific Rim economies being focused on here are only a modest fraction of the global economy. The very slight decline in the energy use rate trend towards mid century shown in Figure 3 for the temperate region is a response to the increasing costs of using fossil fuels. For the United States, on the other hand, extrapolation of a continuation of the trend of historical growth in energy use is a reflection of more rapidly increasing GDP and population. The same is true, even more so, of the tropical region.

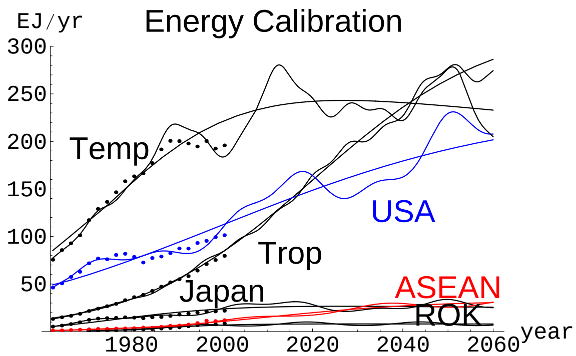

Fig. 3. Biennially averaged energy use rates (points) and fits with periodic variations (curves with multiple maxima) and the background trends with periodic corrections removed (other curves) vs. Julian year from the year 2000.

The trend for Japan shown in Figure 4 is similar to that for the rest of the non-U.S. temperate zone shown in Figure 3. For the ROK, the counteracting effects of economic growth and increasing fossil fuel costs are even more nearly in balance. Not surprisingly, however, the extrapolated energy use growth trend in the currently less developed ASEAN region more closely parallels that shown for the tropical region in Figure 3.

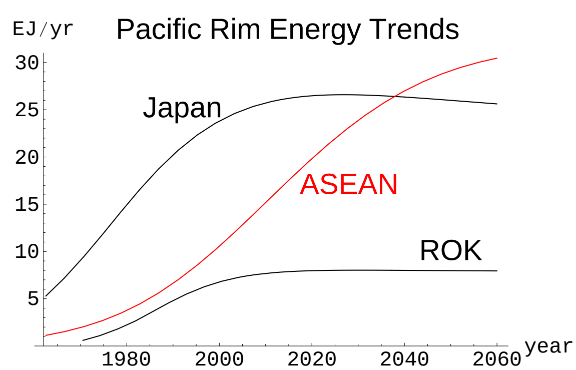

Fig. 4. Background trends as in Figure 6, on an expanded scale with periodic corrections removed.

III.A. Fossil Fuels

Figures 5 and 6 show extrapolations of the total use rate trends for fluid fossil fuels (i.e. oil and natural gas). Economic development in the tropical region produces a growing demand for fluid fossil fuels despite their increasing cost. The United States and the temperate region plotted in Figure 5 exhibit peak use of fluid fossil fuels in the first half of the twentieth century. A breakdown of fluid fossil fuel use into oil and natural gas done for a separate study is consistent with the expectation that a peak in global oil production is likely to be the leading driver of this phenomenon, with a peak in natural gas use rate coming later. The declining use of fluid fossil fuels throughout this century for Japan and South Korea results only from extrapolation of historical trends and does not account for possible unique future events such as the construction of a natural gas pipeline connecting Japan or possibly even Korea to Siberia. Such developments might delay peak use of fluid fossil fuels in Northeast Asia until later in the century. Consistent with its stronger growth in total energy use, increasing ASEAN use of fluid fossil fuels persists well into the first half of the century in these extrapolations. This is consistent with the availability of oil and plentiful natural gas resources in some of the ASEAN countries.

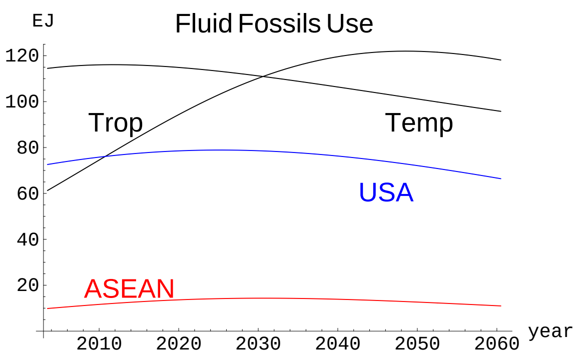

Fig. 5. Extrapolated total annual use trend in exajoules/year of oil and natural gas in the USA and temperate and tropical regions.

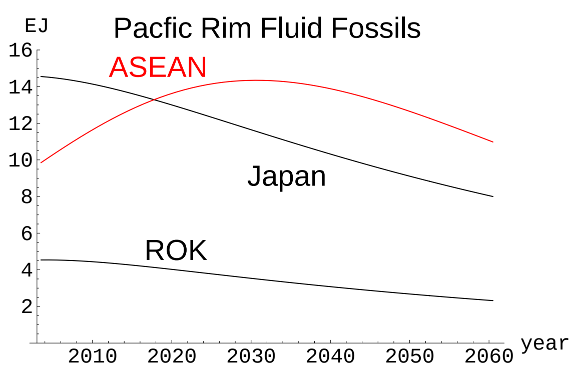

Fig. 6. Extrapolated total annual use trend in exajoules/year of oil and natural gas in Japan, the Republic of Korea, and ASEAN.

Figures 7 and 8 illustrate how historical data are used to calibrate extrapolations of the fraction of total energy coming from fluid fossil fuels. The advantage of fitting energy use fractions as a function of cumulative use is apparent from these figures. Each region follows a similar pattern with a saturating market penetration phase followed by an approximately linear decline of market fraction as a function of cumulative use. This leads to the next question addressed: what fraction of the remaining market is supplied by coal and what fraction comes from sources other than fossil fuels?

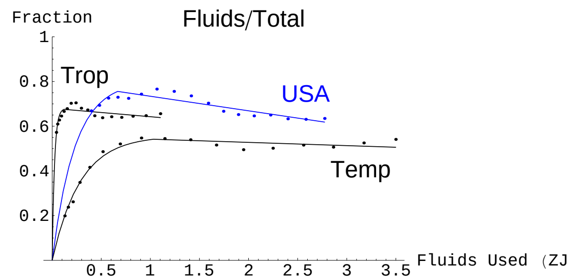

Fig. 7. Observations (points) and curve fits to the fraction of total thermal energy equivalent from oil and natural gas together, as a function of the total amount used in zetajoules (ZJ=1000 EJ) for the USA and tropical and temperate regions.

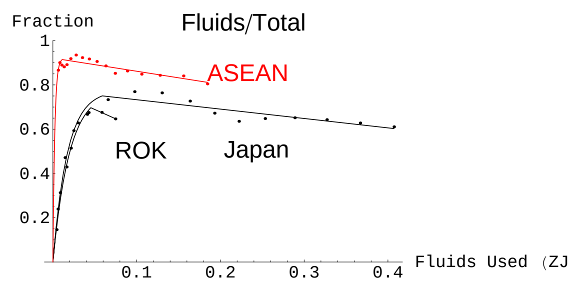

Fig.8. Observations (points) and curve fits to the fraction of total thermal energy equivalent from oil and natural gas together, as a function of the total amount used in zetajoules (ZJ=1000 EJ) for Japan, the Republic of Korea, and ASEAN.

The only forms of energy use considered quantitatively here are fossil fuels and centrally generated electricity. Before the advent of hydroelectric power, all non-fluid-fossil energy of these types came from coal. In some cases, the decline of the coal use rate fraction of non-fluid-fossil energy supply with cumulative coal use in much or all of the twentieth century can be well fit be a piecewise linear curve with at most one break in the slope. For the ASEAN region, however, indigenously produced fluid fossil fuels at one point captured so much of the market that a lot of scatter was introduced in time series data on the evolution of the coal and non-coal shares of the remainder of the market. Nevertheless, to capture the likely long term trend it may suffice to use a linear fit to the coal fraction of this part of the market as a function of cumulative coal use in the ASEAN region. The results of all of these data fits are shown in Figures 9–11.

The extrapolation of ASEAN coal use in the longer term, past the peak use rate in the 2020s shown in Figure 12 below, should be taken only as a rough estimate. The resulting uncertainty may not be particularly important for the initial exploratory stage of nuclear electricity generation in the ASEAN region, but it does raise some question about just what the level of nuclear electricity production will be in the intermediate term in this century before the eventual long term phase out of fossil fuel use during the approach to a sustainable energy future. Indonesia has the largest of the ASEAN region's coal reserves, so a more detailed examination of Indonesia's coal industry might be useful in a subsequent study to shed more light on factors that will influence future competition between coal and nuclear power.

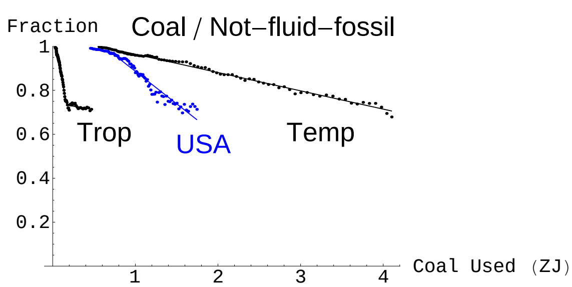

Fig. 9. Observations (points) and piecewise linear fits to the fraction of total non-fluid-fossil thermal energy equivalent from coal, as a function of the total amount of coal used in zetajoules (ZJ=1000 EJ), for the USA and tropical and temperate regions.

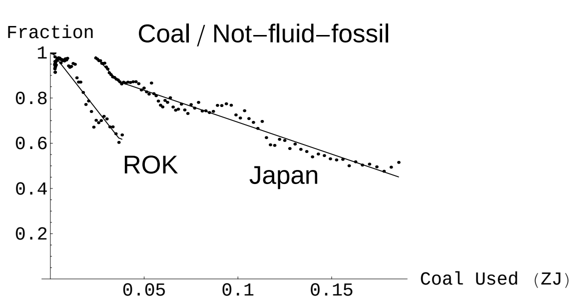

Fig. 10. Observations (points) and piecewise linear fits to the fraction of total non-fluid-fossil thermal energy equivalent from coal, as a function of the total amount of coal used in zetajoules (ZJ=1000 EJ), for the Republic of Korea and Japan.

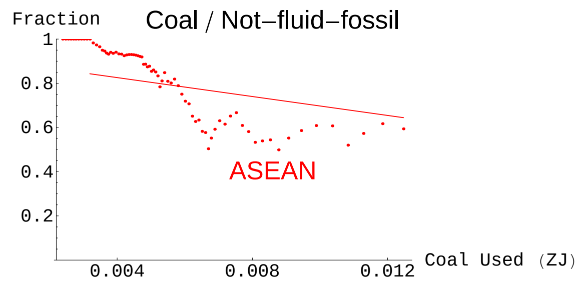

Fig. 11. Observations (points) and a linear fit to the fraction of total non-fluid-fossil thermal energy equivalent from coal, as a function of the total amount of coal used in zetajoules (ZJ=1000 EJ), for the ASEAN region.

The resulting extrapolations of future coal use rate inferred from the fossil fuel market fractions and overall energy use extrapolations are shown in Figures 12 and 13. The developed countries are expected to limit their coal use after the next few decades due to concerns over regional and perhaps global environmental effects.

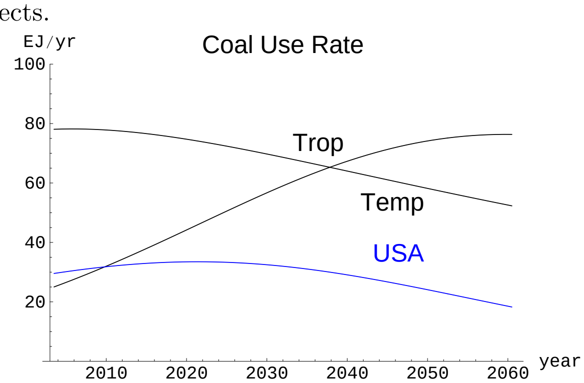

Fig. 12. Extrapolated total annual use trend in exajoules/year of coal in the USA and temperate and tropical regions.

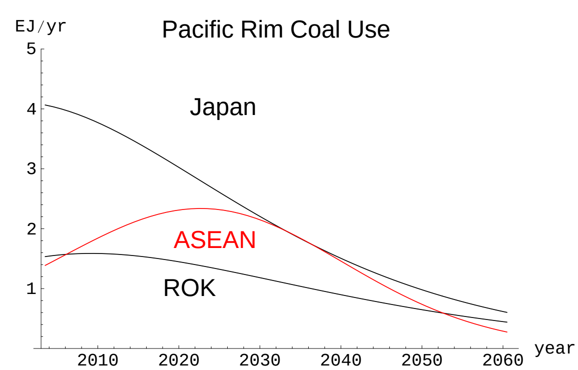

Fig. 13. Extrapolated total annual use trend in exajoules/year of coal in Japan, the Republic of Korea, and ASEAN.

The quantitative extrapolations in Figures 12 and 13 of historical trends confirm the intuitive expectation that developing regions may appreciably lag behind more developed ones in this regard.

III.B. Non-fossil Energy for Electricity

Results for the fraction of non-fossil electrical energy production that comes from nuclear, wind, and solar-thermal generation of electricity are shown for Japan, the United States, and the temperate region in Figure 14. The ASEAN region has no useful data on market penetration by nuclear, wind, and solar-thermal electricity production, so in the ASEAN case one has to evaluate the likelihood of future deployment plans being realized on schedule, as discussed further below. Extrapolations into the more distant future do account for uranium resource depletion for completeness, based on a detailed costing model as described in Rethinaraj (2005), but for the time periods shown in the following three figures uranium resource depletion has a negligible effect.

To get the final desired extrapolations of nuclear energy use requires taking away electricity production by "new renewables" (wind and solar-thermal) from fractions like those shown in Figure 14. South Korea has comparatively little installed water-driven electricity production. The non-water-driven fraction of its non-fossil electrical energy production soon rose to over 0.9 with the introduction of nuclear power. For the tropical region hydroelectricity dominates other non-fossil sources, and there is as yet not enough experience in that region with these other sources to project a significant departure from this situation.

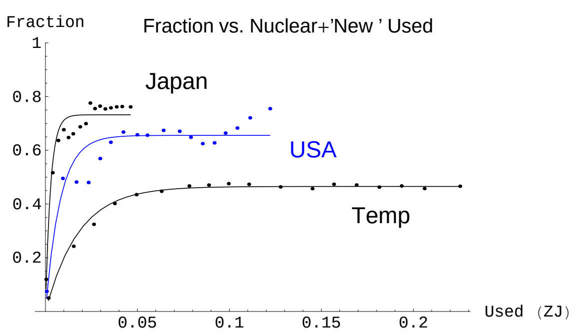

Fig. 14. Observations (points) are for the fraction of non-fossil electrical energy production from the total of nuclear, wind, and solar-thermal sources of the cumulative thermal energy equivalent of these sources used in zetajoules (ZJ=1000 EJ) for the ASEAN region.

For the present cases other than South Korea and ASEAN there is enough historical data to quantify the initial market penetration rate for new renewables. Otherwise we again have to rely on estimates for future deployment plans. On the other hand, the long-term equilibrium market share for new renewables can only be estimated through technology assessment, since there is not nearly enough historical data to be useful for this. For the results shown here we assume that the long term limit fraction for new renewables is thirty percent. The reason is that for both wind and solar electric energy their seasonal and diurnal variability makes it difficult for each to claim more than about a fifteen percent market share. The growth of nuclear energy, after accounting for the modest market share of new renewable electricity generators, is extrapolated in Figure 15 for the United States, the temperate region, and the entire world. (What is plotted in Figure 15 is the fossil fuel thermal energy equivalent of the generated nuclear power as described above, which is nearly but not exactly equal to the thermal energy produced in nuclear power plants.) By mid century the extrapolated nuclear energy use rate total for the world can approach about a fifth of overall global use of all of the energy sources treated here if the strong extrapolated growth in U.S. nuclear energy use is realized. A more detailed breakdown of the various other countries not treated separately but lumped together here in the "temperate" region would likely show a strong contribution from China's plans to build at least half as much nuclear power generation during this century as the United States started the century with.

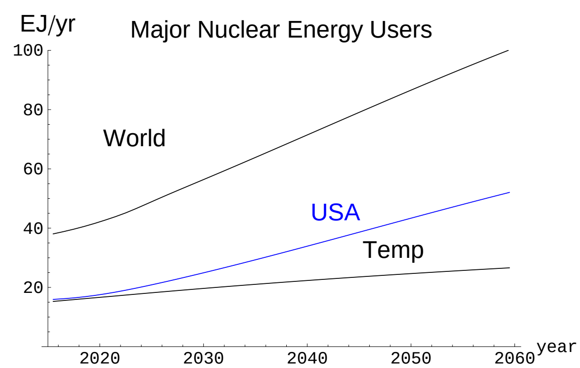

Fig. 15. Extrapolated total thermal equivalent of nuclear energy use rate in exajoules/year in the entire world, the United States, and the temperate region.

As shown in Figure 16, there is stronger extrapolated growth in nuclear energy use in the ASEAN region and the rest of the lower latitude countries lumped together here in the tropical region than for Japan and South Korea. Nevertheless, these two Northeast Asian countries still experience considerable nuclear energy growth as they substitute in non-fossil for fossil fuels. In absolute magnitude the total nuclear energy use rate in these countries remains a small portion of the global total, but there is strong continuing growth in the tropical region's nuclear energy use rate.

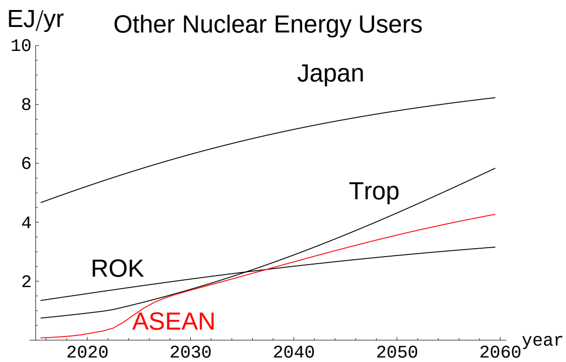

Fig. 16. Extrapolated total thermal equivalent of nuclear energy use rate in exajoules/year in Japan, the Republic of Korea, the ASEAN countries, and the tropical region.

For the particular results shown here, the terminal boundary condition has spent fuel reprocessing just economically competitive with by-product uranium recovery from a large enough resource base to approach essentially an equilibrium state. This condition is compatible with current estimates of the costs of spent fuel reprocessing and recovery of uranium from seawater, albeit with a very large degree of uncertainty in the eventual costs of each. There is a slight transient overshoot of the seventy percent long-term-limit nuclear fraction due to the availability of less expensive conventional uranium ore supplies long after the rest of the system comes essentially to equilibrium. None of this matters appreciably for the results to 2060 shown here, for up to this point the cost of mined uranium remains a very small portion of the total cost of nuclear-powered electricity.

For South Korea, 0.05 EJ/yr thermal equivalent from new renewables can reasonably be estimated for the near future based on current construction plans. For ASEAN we need to look farther into the future for a point where substantial amounts of nuclear and new renewable electric generation capacity are reasonably likely to be installed. For the reference case results shown in Figure 4 for the ASEAN region, we assume four GWe of nuclear plant capacity with an eighty percent load factor and 0.15 GWe of new renewable capacity with a thirty percent load factor in the year 2020. These assumptions are consistent with current plans for two GWe each of nuclear capacity in Indonesia and Vietnam by then and for total new renewable capacity throughout the ASEAN region.

Historical experience suggests, however, delay between early plans for adoption of new electricity generation technologies and their actual implementation. For example, less than half of the reactors listed by the *Commissariat a l'energie atomique* in 1997-98 as planned for operation in or before 2011 showed up in 2005-06 reports as under construction with planned completion by that time. Of those reactors or suitable replacements with expected completion dates, the average delay from original expected completion was over four years (CEA, 1997, 1998, 2005, 2006; World Nuclear Association, 2006). In light of this experience, Figure 17 compares extrapolations for ASEAN region nuclear reactor deployment for the reference case described above to that for the target of four GWe of installed nuclear capacity not reached until 2025. For this graph the results are plotted in GWe of installed capacity rather than EJ/yr thermal equivalent production as above, in order to show more directly how installed nuclear capacity may evolve. The upper and lower curves in Figure 17 are respectively reasonable estimates for the maximum and more likely growth of nuclear installed capacity over the next two decades. Here "more likely" only means more likely than the maximum extrapolated result and should not be interpreted to mean "most likely" particularly with respect to the rapid growth in nuclear energy use following its first introduction in the ASEAN region. Indeed, a minimum and quite possible curve over the time period shown is simply constant at zero. For the so-called Asian flu financial crisis of 1998 has already once stalled nuclear deployment plans in Indonesia. Also, a fully constructed Philippine nuclear plant was converted to natural gas before use. There is no guarantee that similar or other impediments will not be encountered that could delay the first nuclear electric power coming online in the ASEAN region until after well after 2025.

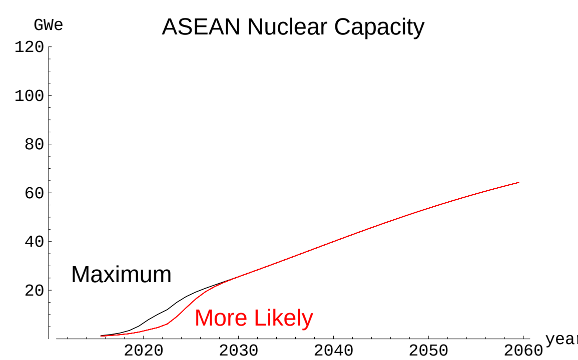

Fig. 17. Extrapolated ASEAN nuclear reactor deployment for four GWe reached by 2020 or 2025.

IV. SPENT NUCLEAR FUEL ARISINGS

Given that transoceanic shipping of spent nuclear fuel is likely to be delayed by as much as a decade or more after the point the shipped fuel originally produced electrical power, the disparity between received ASEAN and U.S. spent nuclear fuel arisings for the extrapolations shown here would be more like that shown in Figure 18 (ASEAN as a percentage of U.S. for ten year delay between fuel burn and spent fuel shipping). This result helps elucidate two conclusions that are important concerning the possible interaction of the United States and ASEAN countries in a global nuclear energy partnership, given that the future of U.S. spent fuel management also cannot be precisely projected.

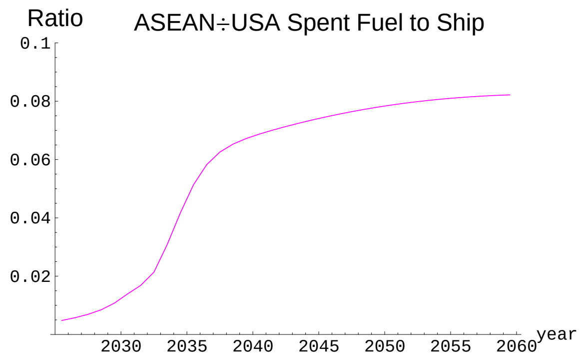

Fig. 18. Extrapolated ratio of ASEAN to U.S. spent nuclear fuel arisings with a ten year delay between power generation and spent nuclear fuel shipments, for the curve labeled "more likely" in Figure 20.

The first conclusion drawn here follows from the observation that any ASEAN spent nuclear fuel shipments are likely to be small compared to U.S. spent fuel arisings for a very long time to come. This means that it should be technically manageable to accommodate such shipments into any well organized spent nuclear fuel management system that may be developed for the United States. This is important, because the time scale for deployment of a full fleet of U.S. actinide-burning fast-neutron-spectrum is inevitably both long and uncertain, given than no fast reactor has yet been operated anywhere continuously in plutonium burning mode at more than a lifetime average of forty-five percent load factor (CEA 2005, where "load factor" refers to gross electrical energy production divided by product of rated gross electrical capacity and the time from grid attachment to shutdown). While recent streamlined actinide burner designs show promise for realizing substantially higher load factors, qualifying these designs and then deploying a full commercial fleet to burn nearly all U.S. actinide production is almost certain to extend beyond the time horizon shown in the above graphs, and possibly much longer. However, full deployment of actinide burners for use of all U.S. spent nuclear fuel arisings would not be an essential prerequisite for the United States to accommodate part or all of ASEAN spent nuclear fuel shipments at least up to and somewhat beyond the middle of this century. At least as an interim measure, such shipments could also either be reprocessed into mixed oxide (MOX) fuel for thermal reactors or held in dry casks pending a decision on direct disposal or reprocessing.

The second conclusion drawn here is that for the ASEAN case there is a long lead time available before a final decision has to be made on just what to do with any spent nuclear fuel shipments from that region. If ASEAN countries want to begin nuclear power plant operations as early as about 2020, then they will almost certainly choose thermal spectrum reactors for this purpose. The spent fuel from such reactors would most likely not be ready for shipment until the 2030s. If they instead choose an integrated reactor approach with safeguarded on-site reprocessing without plutonium ever being separated from other elements, they will almost certainly wait until the successful operation of such a system has been demonstrated elsewhere—and thus also not be ready for ASEAN deployment and fission product disposal until at least the 2030s. So even in the likely case that such countries will only be willing to participate in some sort of GNEP process if their final power plant radwaste disposal is handled by outshipment, such shipments from the ASEAN region are unlikely to become a serious issue until about the 2030s.

APPENDIX. ANALYSIS METHODS

For each geographical aggregation of data, we maximize the total time-integrated discounted utility of per capita consumption. Population increments over 1820 base values are taken to be proportional to a development index a which evolves logistically from 0 to 1. Utility is taken to be a constant power of per capita consumption. Per capita utility is discounted exponentially at a constant "pure time rate of preference" ρ. Maximizing any constant times an integral maximizes the integral. We maximize

$$\int_{-\infty}^{t} dt\, a\, e^{-\rho t}(C/a)^{1-\theta}(1-\theta)$$

Consumption C is divided by a to make it proportional to per capita consumption, and the per capita utility is multiplied by a to make it proportional to the total per capita utility added up over the entire population. Consumption is final product yield less investment to make up for the sum of depreciation rK of total capital K and the rate $\dot{K}$ of its buildup. Herein, over-barred quantities are dimensional constants, over-tilded quantities vary in time, and other quantities are dimensionless. Units of time for dimensionless constants are the "capitalization time" $\bar{t} = 1/(\bar{r} + \bar{\rho})$. The overdot represents rate of change with respect to time when time is measured in units of $\bar{t}$. Dimensionless capital is measured in units of its long term limit value for each region and consumption and production in units of the ratio of this limit capital to $\bar{t}$. Final gross domestic production per unit time is represented as Y/α

where $Y = (a^\eta((1-\beta k)K)^\alpha((1-\beta l)a)^\omega)^\varphi w^\beta$. Here βk and βl are the fractions of capital and labor applied to energy production $w = pa^\zeta(kK)^\alpha(la)^\omega$. Assuming $\alpha+\omega=\beta+\varphi=1$, total production has constant returns to labor, capital, and energy input, and energy production also has constant returns to scale with respect to capital and labor. For a given stage of development, energy production efficiency $p = 1+(h-1)f$ decreases linearly from an initial value of 2 to limit value of 1. This decrease in the energy production efficiency factor p occurs as dimensionless carbon intensity f decreases from an initial value of 1 to approach a limiting value of 0. We use a piecewise linear approximation to the dependence of f on cumulative fossil carbon use u. The above integral is maximized subject to the constraint that the rate of depletion of fossil carbon is equal to its rate of use for primary energy production.

For population proportional to a logistic function a, the population growth rate is $\dot{a}/a = \nu z = \nu(1-a) = \nu z$ where $\nu = \bar{v}\bar{t}$ is a dimensionless constant. In terms of dimensional variables and constants, this equation is $d\text{Ln}[a]/dt = \bar{\nu}z$ where $z = 1-a$ is the "need for development" and $a = 1/(1+\text{Exp}[-\nu t])$, or in dimensional variables $a = (1+\text{Exp}[-\bar{\nu}(\tilde{t}-\bar{t}_0)])$. The constants $\bar{\nu}$ and $\bar{t}_0$ are estimated using time series data for the population growth rate $d\text{Ln}[a]/d\tilde{t} = \bar{\nu}(1-a)$, allowing for statistically significant periodic corrections.

Expansion in three types of parameters is appropriate and convenient. One of these is β, the "capital fraction of energy." Another is the set $\epsilon_k = \bar{w}\bar{t}\bar{m}_k$ of the dimensionless fossil carbon depletion rates for the non-constant portions k=2...5 of the historical and 5,6,7 of the future piecewise linear decline of carbon intensity with cumulative carbon use, where $\bar{w}$ is the long-term-limit energy use rate and $-\bar{m}_k$ is the slope of portion k of this piecewise linear function. The third, denoted $\delta = \nu\theta\xi$ with $\xi = \zeta/\omega$, is proportional to the values ν of the dimensionless ratio of initial population and development growth rate for each region. The details of the expansion in these parameters are given by Rethinaraj (2005). Keeping terms to lowest order in β and ϵ_k for $k > 1$ and through first order in δ, and expressing the results in dimensional form, the result for the rates of fossil carbon use is $\tilde{E} = \bar{E}a^\psi fpF^{\alpha/\omega}$ where $F = (1+\delta a)/(1+\delta)$. and .

The constants $\bar{E}$ (in Gtonne/yr) and the exponents $\psi = 1+\zeta+\alpha\xi$ are calibrated against time series data for energy and fossil carbon use from each region. The constant ξ is calibrated against rate of growth per capita gross domestic product (GDP) with development, given by

$$d\text{Ln}[\tilde{G}_{\text{DP}}/a]/da = \xi + (\alpha/\omega)d\text{Ln}[F]/da$$

(Here $\tilde{G}_{\text{DP}}$ represents GDP increments over 1820 base values.) To accomplish this calibration requires estimates of the capital fraction of production $\alpha = 1-\omega$. It also requires estimates of the constant θ as well as $\bar{t} = 1/(\bar{r}+\bar{\rho})$ to obtain the capitalization lag $\delta = \tilde{v}\bar{t}\theta\xi$ in the lag function $F = (1+\delta a)/(1+\delta)$.

The required numbers $\alpha = 1-\omega$, θ, $\bar{r}$, and $\bar{\rho}$ are assumed for simplicity to be universal constants and are estimated from various types of data in the literature. The labor fraction of production ω is estimated from data on labor fraction of compensation (Golin 2002). The inverse of the inter-temporal substitutability of consumption, θ, is estimated from a regression of international survey data on "happiness" and "satisfaction" upon per capita income (Myers and Diener 1995), taking this survey data to be the most direct available measure of the utility of per capita consumption. Since the capital depreciation rate $\bar{r}$ is also taken to be a universal constant, it can be estimated from available time series data available from the United States (Bischoff and Kokkelenberg, 1987). The methods used to make these estimates are described in more detail elsewhere (Rethinaraj 2005; Singer et al. 2007). Based on a theory derived from work of Ramsey (1928) and described for example by Barro and Sala-i-Martin (2004), the discount rate $\bar{\rho}$ is estimated from data on the difference between inflation-adjusted interest rates and rates of growth of per capita income (WDI 2005). This requires a weighted averaging procedure as also described by Singer et al. (2007). Based on this data, a probability distribution for each of the for constants in the set of universal constants $\{\alpha, \theta, \bar{r}, \bar{\rho}\}$ has been derived, but for simplicity only the maximum likelihood values are used here.

Various additional steps taken here for computational convenience also help avoid a situation where there are known to be statistically significant nonperiodic nearest neighbor correlations between temporally adjacent residuals between theoretical fits and data. In the case of population and per capita GDP, logarithmic differences are taken to eliminate the need for determining an additional dimensional scale parameter in the fits. This has the additional effect of reducing otherwise expected nearest neighbor correlations. In the case of carbon intensity, data points are averaged in groups of at least two, in order to achieve a uniform spacing in cumulative carbon use as the independent variable. In each of the seventeen time-series calibrations done, the results pass the statistical test for nearest neighbor correlation from Wei (1990, p. 23) using the criterion that each of seventeen test statistics be greater than $1-(1/2)^{1/17} = 0.04$.

Methods for calibration, sampling, and near-term extrapolation of fossil carbon use rates for each region are Singer et al. (2007). To produce these results, it is necessary to solve the fossil carbon balance equation, which in dimensional variables can be written in the form

$$\bar{\nu}zad\tilde{u}/da = \bar{w}\tilde{f}_k(1+bh\tilde{f}_k/\bar{f}_1)a^\psi F^{\alpha/\omega}$$

Here $\tilde{f}_k = \bar{f}_k - \bar{m}_k\tilde{u}$ and $b = (h-1)/h$. Also, $\bar{\nu}$ is the initial population and development rate for each region in 1/yr, $\tilde{u}$ is its cumulative carbon use in Gtonne, $\bar{w} = \bar{E}/\bar{f}_1$ is its long-term limit energy use rate in EJ/yr, and $\tilde{f}_k$ are the intercepts of the piecewise linear approximations to the carbon intensity of energy use plotted as a function of cumulative carbon use. The constant $\bar{f}_1 = 0.02547$ Gtonne/EJ is the nominal intensity for earliest times when only coal was used as a primary energy source as operationally defined here. The left hand side of the equation for $\bar{\nu}zad\tilde{u}/da$ results from the property $d/d\tilde{t} = \bar{\nu}zad/da$ of unit logistic function a, where $z = 1-a$. The right hand side accounts for the assumption that the energy production efficiency for a given level of development decreases in the limit of maximum cumulative carbon use by a factor of h. This results because $b(h-1)/h$ and $p = (1 + bh\tilde{f}_k/\bar{f}_1)$ takes on the value h at the beginning when $\tilde{f}_k = \bar{f}_1$and the value 1 in the energy sustainability limit where $\tilde{f}_7 \to 0$.

After expanding in δ to obtain $F^{\alpha/\omega} \approx (1 - z\delta\alpha\omega)$, the fossil carbon balance equation can be analytically integrated to give the result

$$\mathrm{Ln}[\frac{(bh\bar{f}_k/\bar{f}_1)+1/(1-\tilde{u}\bar{m}_k/\bar{f}_k)}{(bh\bar{f}_k/\bar{f}_1)+1/(1-\bar{u}_4\bar{m}_k/\bar{f}_k)}] = \epsilon_k(S[a] - S[a_4])$$

where $S[a] = \int_0^a da\, a^{\psi}(1+\delta a)^{\alpha/\omega}/za$. The integral S can be conveniently expressed as an incomplete Beta function or as a^{ψ} times a special function known as the Lerch transcendent. Here the last historically determined development index break point a_4 for each region and the cumulative carbon use $\bar{u}_4$ at this break point is known from the carbon intensity fitting procedure. The fossil carbon balance equation can be solved for $\tilde{u}$ and the result inserted into the expressions for carbon intensity $\tilde{f}_k$ and the production efficiency factor p to provide an expression for the carbon use rates $\bar{E}\tilde{f}_k(\bar{f}_1 + bh\tilde{f}_k)a^{\psi}F^{\alpha/\omega}$.

The integral of total discounted per capita utility of consumption is maximized subject to the material balance constraint for carbon utilization. In dimensionless variables, the above-mentioned material balance constraint for each region is $\dot{u} = \epsilon_k f w$, where u is the ratio of cumulative carbon utilization to its long-term limit value, f is the ratio of the carbon intensity of energy production to its initial value, w is the ratio of energy use rate to its long term limit value. Defining $\mathcal{L} = a^{\theta}e^{-\rho t}\, C^{1-\theta}\big/(1-\theta) + \kappa\beta a^{\theta}e^{-\rho t}C^{-\theta}(fw - \dot{u}/\epsilon_k)$, the maximization of the integral given at the start of this Appendix is accomplished by solving the Euler-Lagrange equations

$$\frac{\delta\mathcal{L}}{\delta k} = \frac{\delta\mathcal{L}}{\delta l} = \frac{\delta\mathcal{L}}{\delta f} = \frac{\delta\mathcal{L}}{\delta u} - \frac{d}{dt}\left(\frac{\delta\mathcal{L}}{\delta\dot{u}}\right) = \frac{\delta\mathcal{L}}{\delta K} - \frac{d}{dt}\left(\frac{\delta\mathcal{L}}{\delta\dot{K}}\right)$$

Expansion of these equations in the parameters introduced above and applying regularity boundary conditions in the limits $a \to 0$ and $a \to 1$ gives the analytic solutions used here.

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