Can Nuclear Power Supply Clean Energy in the Long Run?

A Model with Endogenous Substitution of Resources

by

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Abstract

This paper models nuclear energy by developing a dynamic model with endogenous substitution among polluting nonrenewable resources. We find that continued expansion of nuclear capacity at historical rates is likely to cause a scarcity of uranium and make nuclear power costlier than other energy sources. Nuclear power can at best supply significant amounts of carbon free energy for the next few decades. But beyond that timeframe, other technologies must kick in. Renewables such as solar, wind and biomass, clean coal and next generation nuclear power may supply significant amounts of energy late this century. The cost of generating low carbon energy increases sharply if global carbon concentration targets are set at 450 ppm instead of 550 ppm.

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1. Introduction

Nuclear power accounts for a sixth of all electricity production globally. Seventeen countries depend on it for at least a quarter of their electricity (World Nuclear Association, 2003). The United States has 103 plants that generate 20% of its electricity. France has 56 of them that account for 80% of electricity supply. Global nuclear generation capacity has exhibited double digit growth in recent years and continues to grow rapidly in the developing countries. About 36 new reactors are under construction. China which has 9 plants, expects to build 30 more in the next 15 years.

Even though the developed countries have not built any new nuclear plants for some time, there is a resurgence of interest in nuclear power as a clean alternative to polluting fossil fuels. The ratification of the Kyoto Protocol into a binding international treaty has revived interest in non-carbon energy alternatives including nuclear energy. Limiting the use of carbon-emitting fossil fuels such as coal, oil and natural gas which currently account for 85% of global energy consumption will mean increased use of nuclear energy, since hydro and renewable energy sources can not supply large volumes of baseload power. In the U.S., nuclear power has been used to replace coal to meet standards set by the Clean Air Act, especially in the Northeast.[2]

This paper develops a long run model of energy substitution to examine the role of nuclear power as a source of clean energy supply. The economic modeling of nuclear power presents several

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[2] "Most of the avoided carbon dioxide emissions over the last 20 years have come from nuclear power," according to a U.S. Department of Energy official (Moniz, 1999).

methodological challenges. Major energy resources such as oil, gas and coal are nonrenewable, and their cost of extraction must increase with cumulative depletion. But nuclear power is strictly not a nonrenewable resource. Its major input uranium is nonrenewable, but the output (reprocessed uranium and plutonium) can be re-used as input. This recycling of materials must be an important feature of any model of nuclear energy. We consider several scenarios – no growth in nuclear and continuation of recent growth trends as well as cost reductions and technological change both in the nuclear industry and in conventional and renewable energy sectors. These cases are examined with and without environmental regulation in the form of caps on aggregate carbon emissions, such as those dictated by the Kyoto Treaty.

There are relatively few studies of the long-run economics of nuclear energy. Cropper (1980) has examined a theoretical model of the trade-offs between fossil fuels and nuclear energy. Most energy models tend to assume the availability of nuclear energy at given prices, but do not account for the uranium used, which turns out to be a critical issue, as we see in this paper. Nordhaus (1979) pioneered the endogenous substitution approach in partial equilibrium to examine the impact of OPEC-induced oil price shocks on the U.S. economy and subsequently Chakravorty *et al.* (1997) modelled cost reductions in solar energy due to exogenous research and development.

A major finding is that nuclear power can help reduce carbon emissions over the next few decades. However, the rising cost of uranium will ultimately make it costlier relative to new coal technologies and renewables. Only major developments in nuclear technology in the form of fast breeders could supply a significant share of energy in the long run, i.e., the latter half of this century. Without these new nuclear technologies, the problem of waste accumulation becomes critical. Nuclear power may help us reduce atmospheric carbon, but will give rise to a new problem of storing significant amounts of toxic waste.

We find that a model with endogenous substitution among energy resources leads to a lower estimate of the shadow price of carbon at least in the near term. Most estimates in the literature suggest a range of $100-500/ton of carbon by 2050 (see Fischer and Morgenstern, 2005; Nordhaus, 2007, Edenhofer *et al.* 2007, Clark *et al.*, 2007). We get a price of $30/ton of carbon in 2050 rising to 300s in the year 2100. The 2050 figure is lower than that in other studies, suggesting that nuclear power may have an important role in reducing the price of carbon in the next few decades, but not farther out in time.

Section 2 introduces a simple theoretical model with resource depletion and environmental regulation. Section 3 summarizes the main elements of the empirical model with details and data provided in the Appendices. Section 4 discusses the simulation results. Section 5 concludes the paper.

2. A Dynamic Model with a Cap on the Stock of Emissions

In this section we discuss the Hotelling theory with environmental regulation imposed in the form of a ceiling on the stock of pollution. Such a ceiling may be thought of as a target carbon concentration in the atmosphere (e.g., 550 parts per million). We assume one demand, one polluting nonrenewable resource and a "clean" backstop resource.[3] The main conclusion here is that because of this constraint on the stock of emissions, we may observe the joint use of the two

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[3] The purpose of this model is to develop insights on how a ceiling affects the extraction of the nonrenewable resource.

resources before a complete transition to the latter.

Let the instantaneous utility at time t generated by energy consumption $q(t)$ be given by $u(q(t))$ which is assumed to be strictly increasing and concave in q, i.e., $u'(q) > 0$, $u''(q) < 0$. Both the nonrenewable and the backstop are assumed to be perfect substitutes, so $q(t) = x(t) + y(t)$ where $x(t)$ and $y(t)$ respectively are the consumption rates of the polluting and clean resource.

It is easier to define $X(t)$ as cumulative extraction of the nonrenewable resource. Then we must have $\dot{X}(t) = x(t).$ The unit extraction cost is given by $c_x(X)$ where $c_x{}' > 0, c_x{}'' > 0$. It increases with cumulative extraction at an increasing rate. This is a plausible assumption which suggests that the cost of extraction may increase as deeper or more inaccessible resources are tapped. Let the aggregate known reserves be denoted by $\overline{X}$. Define $\overline{c}_x = \lim_{x \uparrow \overline{X}} c_x(X)$. Then either $\overline{c}_x = \infty$ or $\overline{c}_x < \infty$.

By choosing the appropriate units, we can assume that each unit of the nonrenewable resource generates one unit of pollution. Denote $Z(t)$ to be the stock of pollution at time t, with $Z(0)$ as the initial stock. Pollution increases $Z(t)$, but a portion declines naturally at an assumed rate $\alpha > 0$. That is, the growth of the pollution stock is given by $\dot{Z}(t) = x(t) - \alpha Z(t).$ Define the exogenous ceiling on the stock of pollution to be $\overline{Z}$ with $Z(0) < \overline{Z}$. Then we can define $\overline{x}$ as the maximum consumption rate of the nonrenewable resource if $Z(t)$ equals its ceiling $\overline{Z}$, i.e., $\overline{x} = \alpha\overline{Z}$, and by $\overline{p}_e$ the corresponding marginal utility, so that $\overline{p}_e = u'(\overline{x})$.

Finally, let c_y be the constant unit cost of the abundant backstop resource. Let y_c (analogous to x_c) be the extraction rate for which the marginal utility equals the unit cost of the backstop, i.e., $u'(y_c) = c_r$. The social planner chooses extraction rates of the two resources to maximize welfare as follows:

$$\max_{\{(x(t),y(t)\}} \int_0^\infty \left\{ u\left(x+y\right) - c_x(X)x - c_y y \right\} e^{-\rho t} dt$$

subject to the two differential equations $\dot{X}(t)$ and $\dot{Z}(t)$, and given values of $\bar{X}, Z(0)$ and $\bar{Z}$. The current value Lagrangian is

$$L(t) = u\left(x+y\right) - c_x(X)x - c_y y - \lambda(t)x + \mu(t)\left[x - \alpha Z\right] + \upsilon_x[\bar{X} - X] + \upsilon_z[\bar{Z} - Z]. \qquad (1)$$

The first order conditions are

$$u'\left(x+y\right) \le c_x - \lambda(t) - \mu(t) \quad (= \text{if } x(t) > 0), \text{and} \qquad (2)$$

$$u'\left(x+y\right) \le c_y \quad (= \text{ if } y(t) > 0). \qquad (3)$$

The dynamics of the co-state variables is determined by

$$\dot{\lambda}(t) = \rho\lambda(t) + c_x{}'(X)x + \upsilon_x(t), \text{ and} \qquad (4)$$

$$\dot{\mu}(t) = \left(\rho + \alpha\right)\mu(t) + \upsilon(t), \quad \upsilon(t) \ge 0, \qquad (5)$$

with $\upsilon_x(t)\left[\overline{X}-X(t)\right]=0$ and $\upsilon_z(t)\left[\overline{Z}-Z(t)\right]=0$. Here $\lambda(t)$ is the shadow value of cumulative extraction and is negative. In other words, the scarcity rent of the resource is $-\lambda(t)$ and $\mu(t)$ is the shadow price of a unit of pollution stock, also negative. Lastly, the transversality conditions are $\lim_{t\uparrow+\infty} e^{-\rho t}\lambda(t)X(t)=0$ and $\lim_{t\uparrow+\infty} e^{-\rho t}\mu(t)Z(t)=0$.

The necessary conditions can be interpreted easily. Condition (2) equates the marginal benefit of an additional unit of the nonrenewable to its total marginal cost, which includes the unit cost of extraction c_x, the scarcity rent $-\lambda(t)$, and the externality cost $-\theta\mu(t)$. Equation (3) equates the marginal benefit from using the backstop to its unit extraction cost c_r and (4) and (5) show how the shadow costs of resources and pollution grow with time. Shadow price $\mu(t)$ must increase at a rate equal to the sum of the discount rate and the natural decay rate of pollution except when the ceiling is binding, in which case the value of the constraint $\upsilon(t)$ is non-zero. Finally at the end of the planning horizon, the value of the resource and pollution stocks must also go to zero.

We avoid technical details and only present a sketch of the possible solutions of the model.[4] If the cost of the backstop is higher than the maximum extraction cost $\overline{c}_x$ then obviously all the resource will be exhausted. Then each unit of the resource may have a differential rent as well as a scarcity rent. It can be shown that there may be only three solutions, if we assume that the cap on the stock of pollution must bind, at least over some interval of time. If not, we are in a pure Hotelling world. The solution that matches with the empirical model in the following sections of this paper is shown in Fig. 1. The polluting fossil fuel is used until the ceiling is hit, and exactly at that

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[4] The complete theoretical characterization is available from the authors. For a similar model but with constant resource extraction costs, see Chakravorty et al (2006).

instant, the clean backstop becomes economical. Both resources are used at constant rates until the fossil fuel is exhausted. Beyond this point, only the backstop supplies energy and the stock of pollution decreases from the regulated level to zero.

The curve MC_A represents the unit extraction cost plus the shadow price of the non-renewable over time absent environmental regulation. This is the Hotelling model with no pollution. The polluting resource is consumed from the beginning until time Γ, when it is exhausted and the backstop is used at rate y_c. The curve MC_B represents the marginal cost of the non-renewable with the ceiling constraint, and includes its extraction cost and the shadow price plus the shadow price of pollution, i.e., the right hand side of equation (2). MC_B increases to equal the cost of the backstop c_y at time t_1. At this time, the stock of pollution also reaches the ceiling. However, at price c_y, demand is too high to be satisfied only by the nonrenewable without violating the ceiling, hence some backstop is used. From t_1 to t_2 the pollution level is at its maximum. The extraction rate of the non-renewable is the maximal rate $\bar{x}$, and the marginal costs MC_B and c_y are equal. The addition to the stock of pollution equals the natural decay, $\bar{x} = \alpha \bar{Z}$. The non-renewable gets exhausted at t_2 and the backstop supplies all energy. The ceiling is not binding from time t_2, and the stock of pollution declines gradually to zero. Beginning from t_2 the shadow price of pollution is zero, and MC_B is higher than c_y. Hotelling scarcity rents in the model with regulation, depicted by MC_C, are naturally lower than in the unregulated case, MC_A.

Equilibrium quantities are shown in the lower graph of Fig. 1. The dashed curve corresponds to the pure Hotelling path without regulation. Resource extraction declines to y_c at time Γ, followed by use of the backstop. The solid lines show resource use under regulation. Note that $t_1 < \Gamma < t_2$. Regulation initially slows down the extraction rate of the non-renewable until Γ, but extends the time period during which it is used, since cumulative demand in both cases must equal the initial stock. If the maximal pollution rate $\bar{x}$ is larger than y_c, only the non-renewable will be extracted at the ceiling followed by a Hotelling-type transition to the backstop resource. Two other solutions can arise depending on parameter values, although we do not discuss them here. For instance, if the backstop is costly, there may be only coal use at the ceiling, followed by a phase with rising coal prices but the pollution stock strictly below the ceiling, and finally a transition to the clean backstop resource. Or the backstop may become economical exactly when the ceiling period ends, and at that instant, coal also gets exhausted. Since $c_y < \bar{c}_x$, exhaustion implies that there is coal that is costlier to exploit than the backstop, which is never exhausted.

The main point of the above model is to show that when a ceiling is imposed on the stock of pollution, extraction may increase for a time, then stay at the ceiling when both the fossil fuel and the clean resource are used simultaneously until the former is completely exhausted.

3. The Simulation Model with Fossil Fuels and Nuclear Power

In this section, we apply the framework outlined above but with several nonrenewable resources and demands, nuclear technology with recycling of materials and backstop resources. We outline the main economic features of the model and provide details of the model and data in the Appendices. The supply side of the model is shown in a schematic in Fig. 2.

Primary energy is provided by two types of resources – nonrenewable resources, namely, crude oil, coal, natural gas and uranium; and renewable energy sources, namely, biomass, wind and solar. These resources can be used to produce electricity or refined petroleum products. All conversion processes from resources to these two secondary energy sectors incur costs of conversion and losses, e.g. through electricity transmission.

In the electricity sector**,** we assume that existing fossil fuel-based power plants will not be replaced by the same designs because of their poor efficiency and environmental performance. Rather, they will be progressively phased out so that their current capacity is exogenously decreased, i.e. their production is reduced to zero within 30 years.[5] Future electricity units from gas and coal will be supplied by more efficient and cleaner plants, if they are competitive relative to other energy sources. These new gas and coal plants use NGCC and IGCC technology (see IPCC (2005)). [6] They could also be endowed with scrubbers for controlling carbon emissions. These plants are called CCS plants (Carbon Capture and Storage).

Refined petroleum products can only be supplied by the three fossils fuels as well as biomass. If crude oil is expensive, transportation energy can be provided by liquefaction of coal, gas and biomass. The direct use (combustion) of gas, coal and backstops completes the set of secondary energy carriers available for final energy consumption.

Final energy demand is divided into transportation, industry and residential/commercial. The energy consumed in the industry and residential/commercial sectors is modeled as a convex

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[5] This is reasonable because electric plants generally have a lifetime of 30 or so years.

[6] Natural Gas Combined Cycle (NGCC) plants are the new standard for gas power stations in North America and Europe. Coal Integrated Gasification Combined Cycle (IGCC) is considered to be the leading technology candidate for electricity production with coal (see MIT, 2007).

combination of electricity and non-electric energy as in Manne *et al.* (1995), with a CES specification that accounts for imperfect substitutability between the two inputs. The non-electric energy supply also follows a CES specification. This bundle comprises energy derived from oil, gas, coal and the backstop if the latter is economical. The energy consumed by the transportation sector can be supplied either by refined petroleum or by a perfectly substitutable backstop in the form of cars powered by solar-powered fuel cells. Note that the sector-specific backstops are entirely carbon-free and renewable. They all consist of fuel cells powered by hydrogen, which in turn is produced by solar-thermal technology.

The three final sectors are characterized by independent demands that are a function of energy prices and income. Generalized Cobb-Douglas demand functions for each sector are given as $D_j = A_j P_j^{\alpha_j} Y^{\beta_j}$, where α_j and β_j are respectively the price and income elasticities for demand in sector j, A_j is the sector-specific technical coefficient, P_j is the price of delivered energy in sector j, and Y is global GDP which is non-stationary. GDP increases exogenously over time at a declining rate as in Nordhaus and Boyer (2000).

Nuclear technology is optimized by choosing the amount of energy produced by conventional Light Water Reactor (LWR) technology. Technical breakthrough in the nuclear sector is modelled by assuming that Fast Breeder Reactor (FBR) technology is available.[7] The nuclear model is embedded in the general model of substitution across resources and demands. We include investment as well as operation and maintenance costs in the transformation of one form

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[7] The LWR is the standard nuclear technology most commonly used. It uses uranium and produces a significant volume of waste. The FBR is generally viewed as a next generation nuclear technology with higher capital costs, prototypes of which are operational. It uses uranium and plutonium and recycles a larger portion of the waste. See Generation IV International Forum: http://www.gen-4.org/ and Appendix for further details of the technology.

of energy into another, e.g., coal into electricity or crude oil into refined petroleum products. These investment costs decline with accumulated experience, as in Goulder and Mathai (2000) and van der Zwaan *et al.* (2002). Operation and maintenance costs are assumed to be constant over time.

Extraction costs for the nonrenewable resources in our model – oil, coal, gas and uranium are assumed to rise with cumulative extraction. The functional form is taken from Nordhaus and Boyer (2000). Cost data are adapted from Rogner (1997). Their intra-marginal units will accrue Ricardian rents. Crude oil extraction costs range from \$3.5/GJ (i.e., \$20/barrel of oil) to \$350/GJ, if the entire stock was exhausted. Initial gas, coal and uranium extraction costs are respectively \$2.5/GJ (i.e. \$2.63/MBtu), \$1.5/GJ (\$0.05 per ton of coal) and \$0.05/GJ (\$20/kg of uranium). If the resource stocks for gas, coal and uranium were exhausted, the cost of gas extraction would go up by a factor of 4, and for coal and uranium by a factor of 7. Conversion costs for each resource into each demand are added to these extraction costs. The backstop resource, solar energy can produce electricity at constant unit cost. It is carbon free.

The model works as follows. The combustion of fossil fuels releases carbon into the atmosphere. Nuclear power is carbon free. LWR technology uses uranium ore as input. FBR technology uses a mix of several inputs, including wastes from LWR production[8]. The algorithm chooses the least cost energy supply for each sector.[9] The two nuclear technologies enjoy complementarities in

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[8] Mori (2000) describes a similar nuclear fuel cycle that allows for waste recycling as well.

[9] Adjustment lags are imposed by providing a lower bound on the rate of decline of each technology. This smoothens the transition in energy supply, as in Manne et al., (1995). For example, electricity production from any given type of plant can only decrease by less than 5% per year. Transitions among non-electric technologies such as a switch from oil to biomass in the production of refined petroleum products, can be faster and are capped at 10% per annum.

materials use and waste recycling and may be deployed jointly. Unlike for fossil fuels, production of nuclear energy creates the need for reprocessing and storage of wastes. Their disposal is costly and must be included in the total marginal cost of nuclear energy. In models where only LWR technology is available, nuclear waste does not have economic value so its shadow price is zero. However, when FBR technology is an option, waste has economic value as input in FBR operation, so it has a non-zero scarcity rent. Consumer plus producer surplus is maximized subject to the technological relationships and stock dynamics. The discount rate is assumed to be 5%.[10]

We consider several scenarios, described as follows:

A. *Stagnation in Nuclear Capacity with No Environmental Regulation*: This model is run with the fossil fuel and renewable resources shown in Fig.2. But the nuclear capacity is fixed at current levels.[11] There is no environmental regulation in the form of a cap on carbon emissions. Even though current trends towards building new plants suggests that nuclear capacity is expected to grow in the near future, we run this scenario mainly to show how the presence of nuclear power affects the utilization of fossil fuels and carbon emissions.

B. *Stagnation in Nuclear Capacity with Environmental Regulation:* The goal here is to show how regulation may affect a carbon standard without growth in nuclear capacity. This scenario imposes a carbon standard of 550 parts per million (ppm) on Model A. Later we perform sensitivity analysis with alternative caps of 450 and 650 ppm as has been done in other studies (e.g., Manne and Richels, 2002).[12] This scenario may represent a policy environment in which

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[10] Newell and Pizer (2003) advocate a low discount rate, 5% or below, for long-run policy analyses.

[11] Nuclear electricity generation in year 2000, the start year of our model, was 9.25EJ or 17% of global electricity generation.

[12] Current CO_2 concentration levels are approximately 380 ppm. A target of 550 ppm is expected to produce some

nuclear power generation makes no headway.

C. *<u>Expansion in Nuclear Capacity with No Environmental Regulation</u>:* This is the case when nuclear capacity grows at a business-as-usual pace. We follow the International Atomic Energy Agency projections for nuclear capacity growth until 2050 (IAEA, 2001, p.21) and extrapolate thereafter. Nuclear capacity is assumed to grow by 2.5% per year until 2020 and by 5% per year until 2050. Overall, capacity increases by about 35% by 2020 and by a factor of 6 by 2050. This increase is in line with the Intergovernmental Panel on Climate Change (IPCC) scenarios discussed by Toth and Rogner (2005) who conclude that the share of nuclear capacity will increase rapidly and represent up to 30 to 40% of total primary energy use by 2100.[13] This model captures a pro-nuclear policy environment. However, only LWR technology is modelled and we do not assume that large scale FBR deployment is feasible in this scenario.

D. *<u>Expansion in Nuclear Capacity with No Environmental Regulation:</u>* This case imposes a carbon standard of 550 ppm on Model C. Between models C and D, the purpose is to see how the carbon standard may affect the transition to conventional nuclear power.

E. *<u>Growth in Nuclear Capacity with availability of FBR Technology, No Regulation</u>:* This scenario assumes that advances in FBR technology will allow significant adoption of this technology along with standard LWR plants. We assume the same aggregate capacity expansion rates as in the above cases. However, because of proliferation issues relating to the large scale adoption of plutonium based reactors, we introduce an aggregate cap on the amount of electricity that can be derived from the nuclear sector. This is set at 10 times the current level of nuclear

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warming but without catastrophic effects (Hoffert *et al.*, 2002).

[13] This is a conservative estimate. Nuclear energy production has grown by a factor of 12 between 1973 and 2000, which is equivalent to an annual average increase of about 12% (IEA, 2001). An MIT (2003) study assumes that nuclear capacity will increase by a factor of 3 by 2050. We examine the effect of a lower (50%) rate of increase later in the paper.

energy production, as in van der Zwaan (2002). The effect of a higher cap is examined in the sensitivity analysis section.

F. *Growth in Nuclear Capacity with availability of FBR Technology and Environmental Regulation:* This is Model E with a carbon cap.

4. Model Results

Energy use: Table 1 summarizes the results from models A to F. A common feature of all these runs is that the proportion of aggregate energy supplied by oil and natural gas does not vary significantly across the spectrum. The share of oil is about 30-32% of aggregate energy in 2050 dwindling to almost zero in the year 2100.

Similarly the share of natural gas in aggregate energy supply is quite robust - within 18-21% across all scenarios and diminishes to an 8-9% share by 2100. Coal shares decline from supplying almost half of all energy under no regulation and no nuclear expansion (model A) to about a third when nuclear capacity expands or a carbon cap is imposed (models C-F). The share of nuclear power in aggregate energy rises from the current 2% to about 14% in a pro-nuclear scenario (models C-F). In line with Bunn et al. (2005), who estimate that recycling nuclear wastes would remain too expensive for at least the next 50 years, FBR proves to be competitive from 2065 on (Models E and F). The share of nuclear energy is then 20% of all energy supplied by the year 2100 (Model F). Mori and Sato (2004) and Toth and Rogner (2006) show that nuclear energy could represent up to a third of total energy needs.

Gas replaces oil in power generation in the medium term, and supplies up to 45% of total primary energy consumption in 2030 before being replaced by coal (not shown in Table). Coal-based or biomass-based fuels progressively substitute for oil in the production of petroleum products depending on whether a carbon cap is in place or not. Oil use is almost abandoned by the end of the century because its progressive depletion causes a rise in oil extraction costs. By the end of our time horizon, the cost of a barrel of oil will have multiplied by a factor of 3.5. Nuclear plays a minor role if its capacity is maintained at current levels. Without environmental regulation, renewable energy also remains a marginal player and only hydropower is economical, the capacity for which is assumed to be constant.

The introduction of environmental regulation decreases aggregate energy consumption because of the added cost of meeting the carbon cap. The share of electricity in the final energy mix increases from 20% to about 33% in the medium term, and higher in the longer term (see Table 1). This occurs partly because the cost of electricity has a bigger investment cost component than non-electric energy. Electricity is thus less sensitive to a rise in fuel costs due to resource depletion and the cost of electric generation rises at a slower rate than for non-electric energy leading to increased substitution in favour of electric energy. Some variations occur across models in the longer term, the electricity share ranging from 38 to 48%. In general, electricity gains “market share” from other sectors under environmental regulation, because it is easier to substitute into low carbon fuels in electricity generation, than say in transportation.

Because electricity is the most important sector in terms of the potential for substitution of low carbon fuels, we next discuss which fuels will emerge as important players under the various scenarios, shown in Fig. 3. The left hand side panels show the scenarios with no carbon cap.

Notice that the bulk of future electricity supplies come from new coal fired generation and nuclear when the model allows for growth in nuclear capacity. Existing coal fired generation and electricity from natural gas decline rapidly as these units are phased out over time. They are replaced by modern coal plants which are more efficient, and their efficiency increases over time from learning-by-doing. The renewable sector is not economical. In the medium term, coal and nuclear (when allowed) dominate but in the long run, nuclear and renewable energies (biomass and wind) are economical. Under environmental regulation, nuclear, coal-fired units with scrubbers (CCS) and renewables supply the bulk of electricity in the long run. If only standard LWR technology is available, nuclear is phased out in the medium run because uranium becomes expensive with depletion. Other studies such as Rothwell and V.D. Zwaan (2003) come to the same conclusion, although without a formal modeling approach. However, new generation FBR technology can overcome this problem by recycling nuclear waste. Allowing for next generation nuclear power proves economical in the long run. FBR replaces coal powered CCS generation.

Waste, Emissions and Carbon Concentration: The competitiveness of LWR technology for power generation and the exhaustion of uranium resources lead to a significant accumulation of nuclear wastes, as seen from Fig. 5 (Model C). Because of reprocessing, waste production is much lower under FBR technology than under LWR technology despite increased nuclear electricity generation. Accumulated nuclear wastes with both LWR and FBR (model E) are 84% lower than the ones with LWR only (Model C).

There is a trade-off between the production of toxic wastes and carbon. Even without a carbon cap, the expansion of nuclear capacity provides carbon-free electricity in the electricity sector so that carbon-intensive fossil fuels can be used in other sectors such as transportation. From model A to C, carbon emissions decline from 14 to 11.3 billion tons in 2050, but they catch up later at about 25 billion tons[14] as nuclear power from LWR becomes expensive (see Table 1).

The heavy dependence on coal in the constant nuclear scenario raises cumulative carbon emissions. The carbon concentration (see Fig. 6) reaches a level of 720 ppm in the year 2100 and 884 ppm in 2150, orders of magnitude that are expected to cause significant damages (Alley *et al.,* 2003). The expansion of nuclear power allows for a slowdown in the increase of atmospheric carbon concentration. Adoption of FBR technology reduces the carbon concentration to 650 ppm at the end of the century (Model E). With a carbon cap, emissions decline and the ceiling is attained with a lag of about 10 years, i.e. in 2090 (check models B and D in fig. 6).

The Cost of Meeting Carbon Caps: The effect of meeting the carbon cap on consumer surplus is shown in table 2. Since models A,C,E do not include carbon caps and successively allow for additional technologies or capacity expansion, the net economic surplus increases going from A to E. For the same reason, models B,D,F must also exhibit increasing surplus. However, it is not clear how imposing a carbon cap and allowing for new energy supply options such as nuclear power will affect the economic surplus. For example, surplus declines when a carbon cap is imposed (A to B) but increased nuclear capacity more than compensates for this reduction (model C). These numbers may seem small but a 1% reduction in energy costs translate into a trillion dollars. Mitigation costs reported by Edenhofer et al. (2007) draw a similar conclusion.

5. Sensitivity Analysis

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[14] This is several times more than current annual emissions of about 7.35 billion tons.

In this section we examine the sensitivity of the results to changes in various cost and policy parameters.

Alternative Carbon Targets: The model is run for carbon targets of 450 and 650 ppm. Oil and natural gas take a higher share of the fuel supply in 2050 and coal a lower share as is to be expected. The 450 ppm scenarios are the only ones where nuclear gains significant market share – 12-15% of the energy mix by 2050 and a whopping 78% by 2100 when no FBR expansion is feasible. This suggests that a strict control of atmospheric carbon concentration will essentially imply that either renewables or the next generation nuclear technologies will likely be the primary fuel, analogous to the role coal plays today. The share of electricity also increases to almost half of total energy supply, simply because of the relative availability of low carbon options in that sector.

Emissions decline significantly under a 450 constraint and 2050 emissions need to be approximately at the same level of today. In 2050, primary energy supply is cut by 25% which lies in the lower range of results compiled by Clarke *et al.* (2007). It is clear that the more stringent the carbon cap, the higher will be the policy[15] cost of meeting clean carbon objectives (see Fig. 8) for each carbon cap. The more stringent the concentration target, the bigger the cost reduction owing to nuclear expansion. Our results are comparable to those of Gerlagh and van der Zwaan (2006) even though they use a general equilibrium model and thus account for macroeconomic adjustments**.** Their costs of stabilization to 450 ppm range from $800-1100 billion, depending on model assumptions and about $100 billion for a 550 ppm target. Our

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[15] Policy costs are computed in the following way: We run the various model specifications with alternative concentration targets. At each date, we are then able to construct the marginal abatement cost curves by plotting the shadow cost of carbon against the emission reduction as compared to the corresponding baseline for the various targets (see Ellerman and Decaux, 1998). We obtain a rising marginal cost curve. By interpolation, we compute the area below the curve. The policy cost is summed over each date and discounted to obtain the overall figure.

respective figures are $800 and $200 billion. Our higher costs may be due to higher long run carbon emissions - our emissions peak at around 12GtC in 2065, while theirs remain below 11GtC. The cost of achieving a 450 ppm target appears much larger than the one for 550, as confirmed by numerous studies (Edenhofer *et al.*, 2006, Nordhaus, 2007, Clarke *et al.*, 2007). Because of climate inertia, the stabilization at 450ppm would require emission declines by 2030 and a rapid transformation of the energy supply mix.

Sensitivity to Other Model Parameters: We briefly review the effect of changes in discount rates, nuclear investment costs, nuclear capacity and parameters for technical progress (see Table 3). We experiment with parameter changes for Model D, where LWR technology is allowed to grow under a carbon cap. The results (see Table 3) are quite robust to significant variations in the discount rate used. The medium run competitiveness of LWR technology is not affected. However it affects the long run shadow price of carbon, which reaches $135/tC in 2100 (instead of $464/tC in model A). This is because as shown in Chakravorty et al. (2006), the shadow price of carbon increases at a rate equal to the sum of the discount rate and the rate of natural pollution decay.

A lower discount rate favors future investments in capital intensive technologies such as wind power. Capital intensive technologies with relatively low O&M costs (such as wind) gain from a low discount rate (see Appendix, footnote 15). This decreases cumulative emissions from 1040 billion tons in Model C to 918 billion tons. Note that low discount rates imply a slower pace of increase of the carbon shadow price and thus a lower penalty on the energy system**.** On the contrary, a higher 8% discount rate tends to delay the introduction of renewable energy for power generation and thus leads to an increase in the shadow price of carbon in the long run (see Table 3).

Alternative investment costs for LWR and FBR do not change results in a significant way. Carbon costs are only slightly affected (ranging from $287-322/tonC in 2100) in Model D. Variations in FBR investment cost affect the levelized cost of FBR technology, and leads to minor changes in the aggregate surplus for Model F, since FBR technology only appears in the long run. To assess the effects of fast technical progress, we assume an across-the-board doubling of learning rates in all technologies. These cost reductions benefit other clean fuels (such as solar energy) and completely remove nuclear power plants from the energy mix. Carbon concentration even stabilizes at a level below 500 ppm leading to a zero shadow price of carbon in 2100. Note that high learning rates also make nuclear power redundant, with a market share of 5% in 2050 which goes to zero by 2100!

A slower (halved) rate of nuclear capacity increase slows down nuclear power penetration as compared to Model D. Nuclear production shifts to the future and peaks in 2095. This results in an earlier and more costly introduction of wind energy, and thus a higher cost of carbon. An alternative (doubled) maximum nuclear capacity increases the share of nuclear power generation and decreases the shadow cost of carbon.

Finally, increasing the availability of uranium (not shown), alters the results only marginally, suggesting that uranium depletion is not the critical limiting factor for LWR expansion. The prospects for increased LWR power generation are hampered by significant investment costs.

Nuclear is replaced by coal which becomes cheaper owing to learning within the same time-span as in Model C. Overall, as summarized in Table 3, the results of the model are quite robust to changes in parameter values.

Fig. 9 shows the carbon emissions per unit energy produced in selected cases. Emissions decline in the short run in model A but go up because there is no nuclear expansion and coal must provide electricity and refined petroleum products. Nuclear expansion (model C) lowers emissions per unit energy in the short run but they do catch up with model A in the long run. A carbon cap (model B) leads to a sharp drop in emissions around 2060 when carbon-free electricity becomes competitive. But with growth in nuclear capacity, this drops occurs much earlier (model D). In general the carbon intensity of energy production is driven mainly by electricity. Other sectors have limited substitution potential under environmental regulation. Fig. 10 shows the ratio of electric to non-electric energy and corresponding carbon emissions for some selected models. Non-electric energy is the sector affected the most by carbon caps, while the contribution of nuclear in reducing emissions can be seen from the middle panel, where aggregate energy use increases significantly, but emissions decline.

6. Concluding Remarks

This paper applies a model with price-induced substitution across resources to examine the role of nuclear power in reducing global warming. The cost of fossil fuels and uranium, the main input in nuclear power generation, rises with depletion. The main insight is that nuclear power can help us switch quickly to carbon free energy, but in the long run, large scale adoption of nuclear power will be hindered by the rising cost of uranium. Only significant developments such as the availability of new generation nuclear technology such as Fast Breeder Reactors may alleviate the problem of toxic waste disposal. Although these plants produce more toxic waste (plutonium), they recycle a significant portion leading to a reduction in aggregate volume. If expansion of nuclear capacity occurs at historical rates, uranium producers could engage in cartel-like behavior since the metal is found only in four countries, fewer than for crude oil. These results are similar to recent engineering studies of the potential of nuclear power as a carbon free source of energy (MIT, 2003).

In the long run, renewable energies such as biomass and wind become economical and supply a large portion of the energy. But significant supplies also come from clean coal technologies. The availability of new nuclear technologies such as Fast Breeders reduces the dependence on clean coal. Meeting carbon concentrations of 550 ppm is modestly costly but a 450 ppm target implies rapid reductions in the near term (by 2050). This sharply raises the cost to the economy. The cost of carbon jumps up from $18 to $150/ton in 2050. This is somewhat lower than predictions by other studies such as the DICE model of Nordhaus who predicts a 450 ppm carbon price of $250/ton in 2050 (Nordhaus, 2007). Clarke et al. (2007) exhibit carbon prices in the order of $500/ton in 2050 or even higher.

It is possible that the price-induced substitution of energy resources causes the estimates to be lower than in the literature. Most studies do not allow for resource scarcity rents and fuel substitution, which may lead to model rigidities that overestimate the shadow cost of the externality. The shadow price of carbon plays an important part in determining which abatement options may be feasible as well as the size of a global permit market. Lower carbon prices may suggest that such a market may be smaller than expected, with lower benefits relative to no trading. The damage to economies that may be potential buyers of carbon, such as the United States, may be smaller than currently estimated. Similarly, potential benefits to sellers of permits such as Russia and Ukraine may be smaller.

Environmental regulation increases the price of carbon-intensive fuels and leads to an expansion of the electricity sector relative to other sectors of the economy, because it is most suited to substitution by cleaner fuels. Substitution in other non-electric sectors such as transportation and residential/commercial energy does not change significantly since substitution is relatively expensive.

The model results are quite robust to changes in cost parameters. However, the results are sensitive to the choice of the discount rate. A lower discount rate (such as 2%) favors capital intensive technologies with relatively low operation and maintenance costs such as wind power. Renewable energy technologies become economical earlier leading to a lower cost of carbon and lower aggregate emissions. Across-the-board higher learning rates also benefit technologies such as solar energy because they have a lower floor. Nuclear power becomes redundant, with a 5% market share in 2050 and zero in 2100.

There are several restrictive assumptions in the model which could be relaxed in future work. The complexity of an empirical model with multiple resources and environmental regulation suggests that the textbook one-resource, one-demand Hotelling model may be inadequate for making a realistic assessment of energy alternatives. More work needs to be done in developing reasonable theoretical extensions of Hotelling to consider important issues such as the recycling of resources. We have also abstracted from considering adjustment costs. Adding nuclear capacity in the form of a new plant or additions to an existing facility takes several years because of licensing and safety permitting procedures. We have assumed frictionless additions to capacity, although they are capped at reasonably low levels. To some extent, imposing a cap on capacity expansion in the model as we have done is a simple way of recognizing the existence of adjustment costs. However, the demand for clean energy far outstrips the potential supply through traditional nuclear power. Thus it is possible that adjustment costs may not make a big difference to the empirical results especially in the long run, although that needs to be checked. Adjustment costs will delay energy transitions between sectors and favor sectors with low adjustment costs such as fossil fuels and solar energy.

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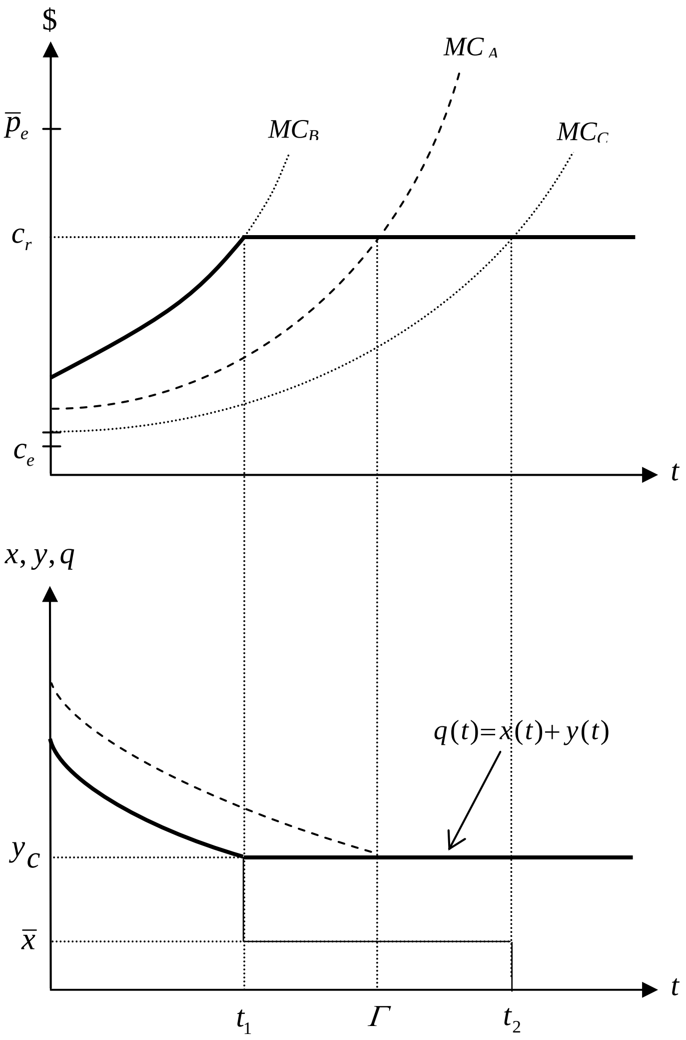

Fig. 1: Both the Polluting Fossil Fuel and the Clean Renewable are used at the Ceiling

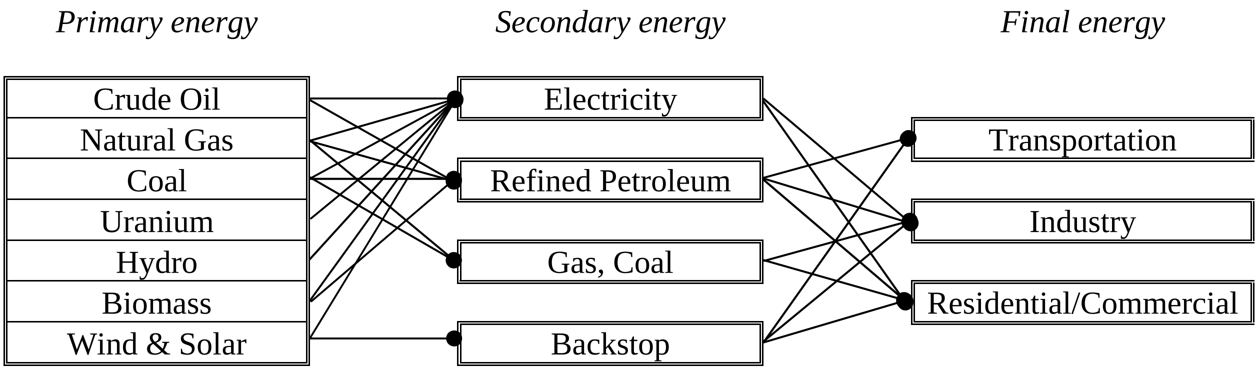

Fig. 2. Schematic of the Energy Model

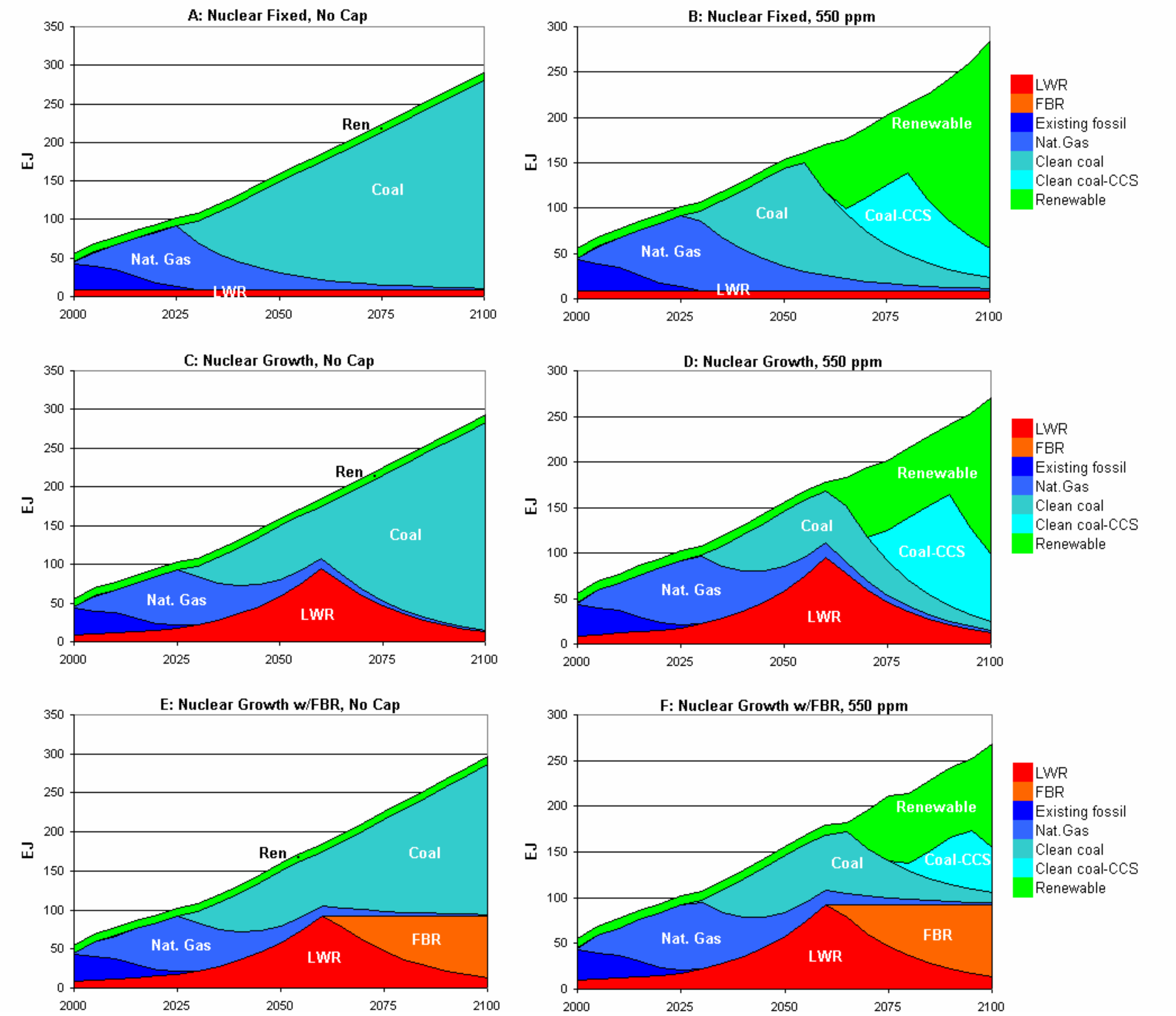

Fig. 3. Electricity Supply under Alternative Scenarios

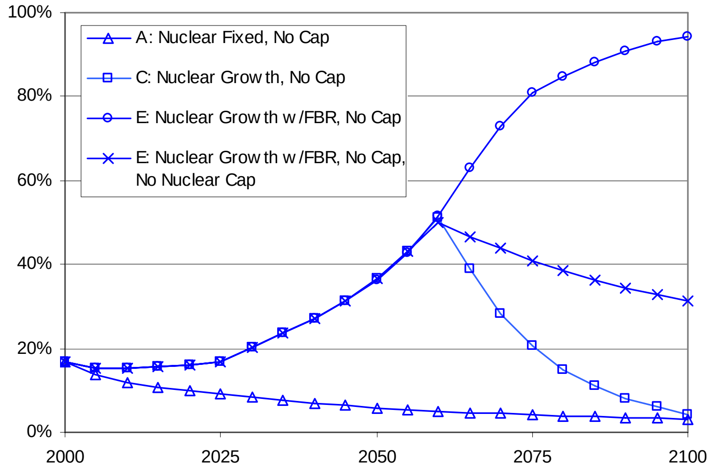

Fig.4. Share of Nuclear Power in Electricity

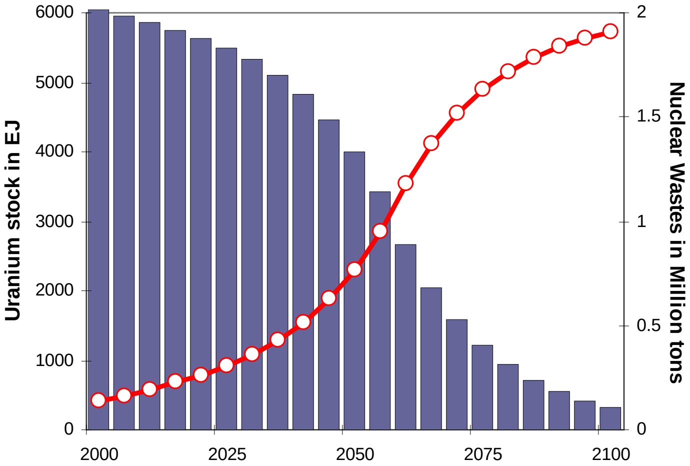

Fig. 5. Depletion of Uranium Stock (bars) and Cumulative Stock of Nuclear Waste (circles) in Model C

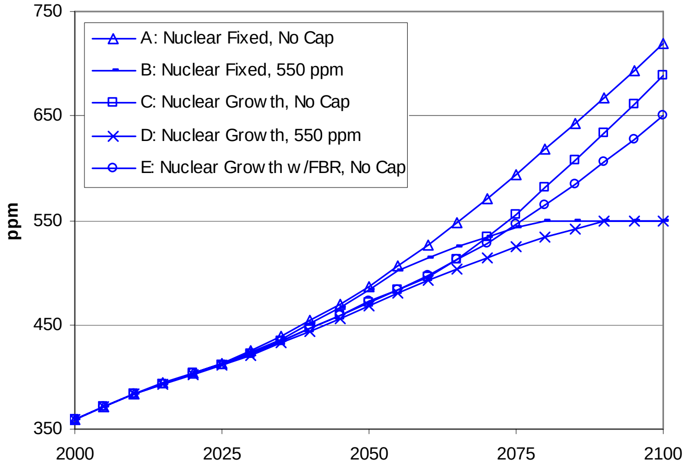

Fig. 6: Time Path of Carbon Concentration

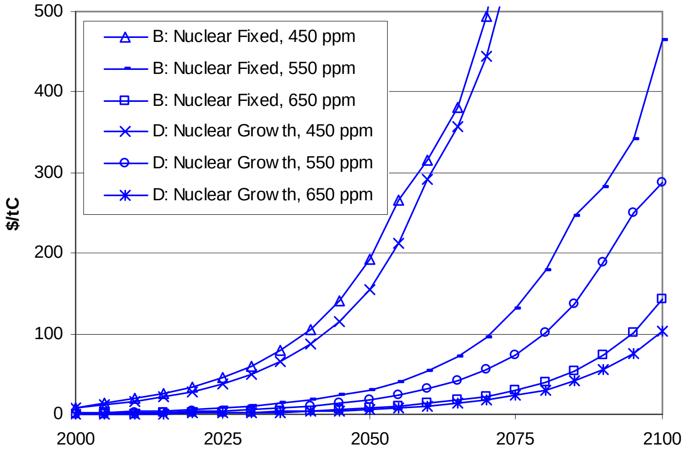

Fig. 7. Shadow Price of Carbon

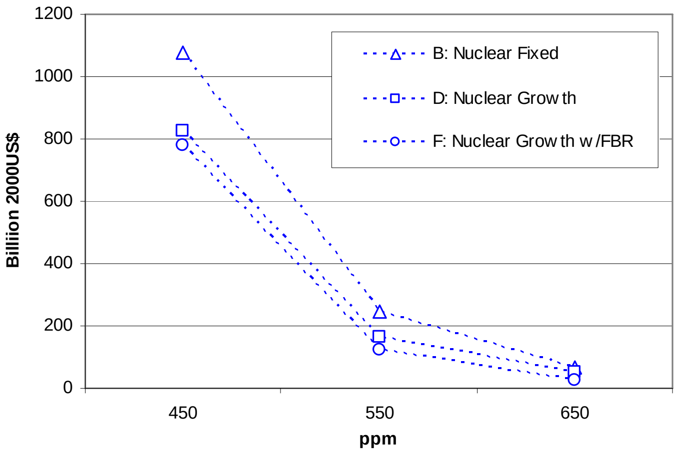

Fig. 8. Costs of achieving different Climate Targets

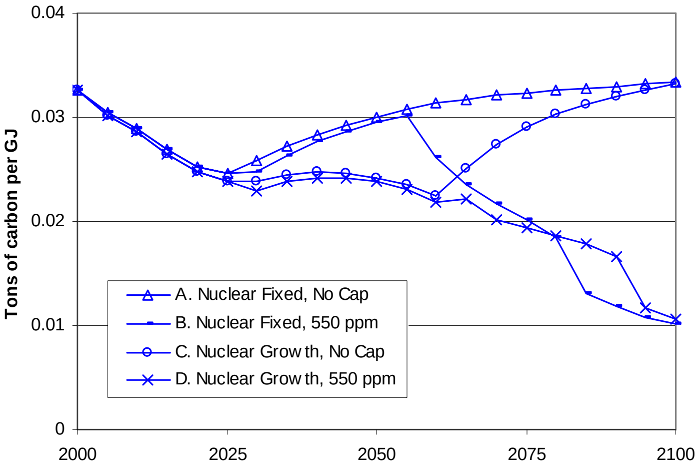

Fig. 9. Carbon intensity of Final Energy (emissions per unit energy)

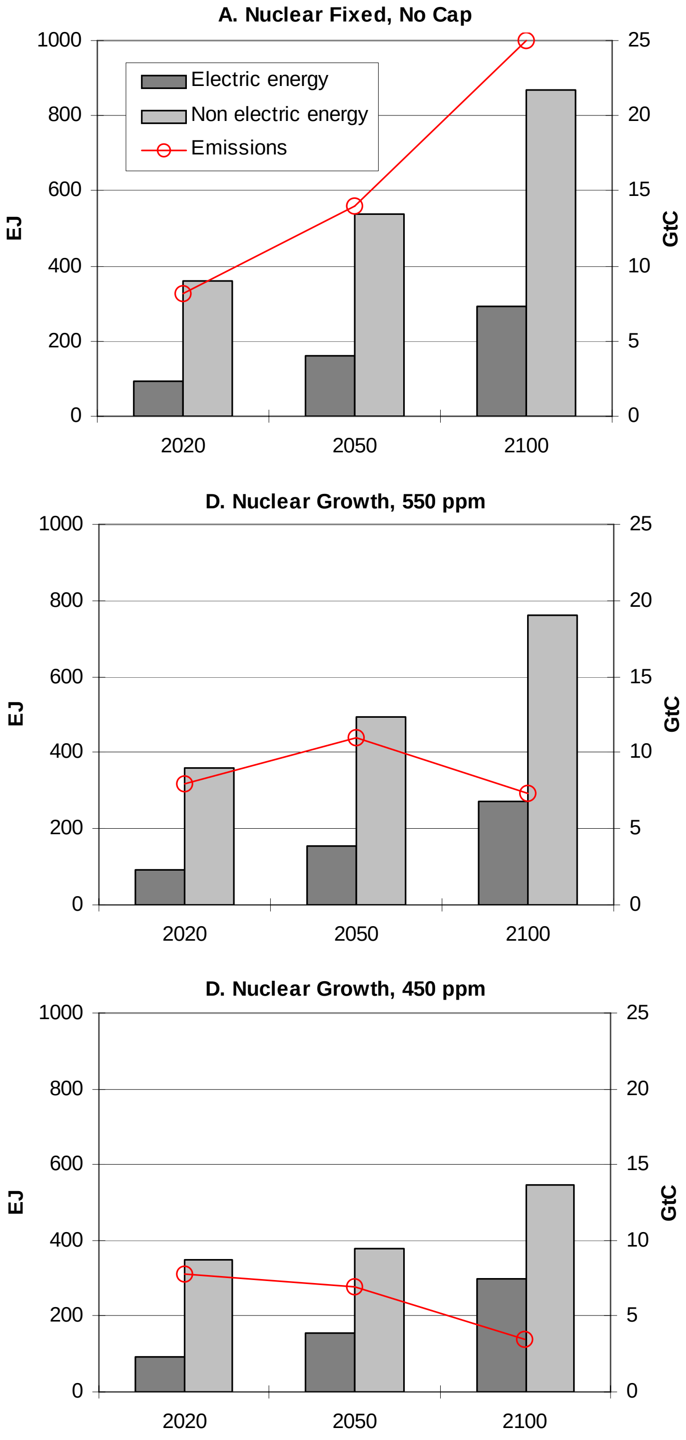

Fig.10: Electric/Non-Electric Energy Use (bars) and Carbon Emissions (circles) for Selected Models

Table 1. Energy Mix, Carbon Emissions and Shadow Prices

			Model A	Model B	Model C	Model D	Model E	Model F
Primary energy use (EJ)		2050	699	678	663	650	664	651
		2100	1159	1024	1165	1034	1222	1043
Share of primary energy by fuel	Oil	2050	30%	30%	31%	32%	31%	32%
		2100	1%	1%	1%	0%	1%	0%
	Gas	2050	18%	20%	19%	21%	19%	21%
		2100	9%	8%	9%	9%	9%	9%
	Coal	2050	49%	46%	34%	32%	34%	32%
		2100	88%	31%	88%	42%	69%	36%
	Nuclear	2050	2%	2%	14%	14%	14%	14%
		2100	1%	1%	2%	2%	21%	24%
	Renewables	2050	1%	1%	2%	2%	2%	2%
		2100	1%	58%	1%	46%	1%	30%
Share of electricity in final energy		2000	20%	20%	20%	20%	20%	20%
		2050	33%	32%	32%	32%	32%	32%
		2100	38%	43%	38%	39%	38%	48%
Carbon emissions (GtC)		2050	14.01	13.46	11.31	10.95	11.34	10.99
		2100	25.03	6.71	25.06	7.27	20.94	7.27
Carbon value ($/tC)		2000	-	2	-	1	-	1
		2050	-	30	-	18	-	17
		2100	-	464	-	287	-	276

Table 2. Energy Production Costs and Net Surplus (in billion $)

	Model A	Model B	Model C	Model D	Model E	Model F
Discounted energy costs	103620	102860	103129	102598	103017	102332
	-	-0.74%	-0.48%	-1.00%	-0.59%	-1.26%
Discounted net surplus	346409	345579	347108	346529	347319	346904
	-	-0.24%	0.20%	0.03%	0.26%	0.14%

Table 3. Summary of Sensitivity Analysis(1)

		Nuclear share in electricity			Shadow carbon cost $/tC			Discounted net surplus relative to Model A
		2020	2050	2100	2020	2050	2100	
Model D	450ppm	16%	38%	4%	28	156	1107	99.46%
Model F	450ppm	16%	38%	31%	28	156	1106	99.59%
Discount rate	2%	16%	39%	5%	16	34	135	307.58%
(Model D)	8%	17%	38%	5%	1	9	576	58.66%
50% Nuclear Capacity	450 ppm	13%	16%	17%	31	173	1078	99.25%
(Model D)	550 ppm	13%	15%	19%	5	24	345	99.91%
Doubling of Learning rate	450 ppm	17%	5%	0%	22	122	667	98.25%
(Model D)	550 ppm	17%	5%	0%	0	0	0	98.52%
LWR investment cost	1600 $/kW	16%	37%	5%	3	18	287	100.09%
(Model D)	2000 $/kW	16%	37%	3%	4	21	322	99.92%
FBR investment cost	1850 $/kW	16%	37%	34%	3	17	276	100.15%
(Model F)	2600 $/kW	16%	37%	34%	3	17	276	100.13%
150% Nuclear Capacity	450 ppm	16%	38%	47%	28	152	1112	99.69%
(Model F)	550 ppm	16%	37%	52%	2	13	244	100.22%

(1) All runs are for a 550 ppm carbon target unless stated otherwise.

Appendix A. Modeling Details and Data

The Energy Model

In this section we provide the detailed specification of the energy model presented in Fig.2. Primary energy is obtained from two types of resources: exhaustible resources namely oil, gas, coal and uranium; and renewable energy resources, biomass, wind and solar. Primary energy is then transformed into secondary energy in the form of electricity, refined petroleum products and backstop energy. These resources plus coal and gas, in turn, are consumed by three final sectors: Transportation, Industry and Residential/Commercial, indexed by $j \in \{T, I, RC\}$.[16]

The energy demand in the final sector j, denoted by $D_j(t)$ at date t is given by $D_j(t) = A_j.P_j(t)^{\alpha_j} Y(t)^{\beta_j}$ where α_j and β_j are respectively the price and income elasticities for demand in sector j, A_j is the sector-specific technical coefficient, P_j is the price of delivered energy in sector j, and Y is global GDP which is non-stationary. GDP increases exogenously over time at a declining rate. Since all variables are a function of time, we omit writing the time subscript when convenient. Energy consumed in the transportation sector, D_T, can be supplied either by refined petroleum products, $dOilP_T$, or by a perfectly substitutable backstop dB_T and can be written as $D_T = dOilP_T + dBackstop_T$ where the subscript T denotes the transportation sector. The energy consumed in the Industry and Residential/Commercial sectors, respectively D_I and D_{RC}, are represented by a convex combination of electric, $dElec_{j\in\{I,RC\}}$, and non-electric energy, $dNElec_{j\in\{I,RC\}}$. We use the calibrated form of a CES production function (see Rutherford, 2002) to account for imperfect substitutability between the two inputs[17]

$$D_{j\in\{I,RC\}} = \overline{Y}_j \left[\theta \left(\frac{dElec_j}{\overline{Elec}_j} \right)^{1-\rho} + (1-\theta) \left(\frac{dNElec_j}{\overline{NElec}_j} \right)^{1-\rho} \right]^{\frac{1}{1-\rho}}$$ where parameters $\overline{Y}_j, \overline{Elec}_j$, $\overline{NElec}_j$ and θ are calibrated against observed data, and ρ is the inverse of the elasticity of substitution. Electricity can be generated by plants indexed by et using resources as shown in Fig.2. The demand-supply balance can be written as $\sum_{j\in\{I,RC\}} dElec_j = \left[\sum_{et} Elprod_{et} \right] \times Eloss$ where $dElec_j$ is the supply of electricity to

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[16] Coal and gas can also be directly transformed into refined petroleum products.

[17] A similar distinction between electric and non-electric energy has been made by Manne *et al*. (1995) in the MERGE model.

sector j , $Elprod_{et}$ is the electricity generated by plant et and $(1-Eloss)$ is the fraction of electricity lost through the distribution grid.

Sectoral non-electric consumption comes from the direct use of petroleum products, $dOilP_{j\in\{I,RC\}}$, gas, (denoted by $dGas_{j\in\{I,RC\}}$), and coal ($dCoal_{j\in\{I,RC\}}$). A CES functional form is used. Because the bulk of fuel substitution is expected to occur in the electricity sector, the modeling approach we adopt focuses on electricity. Non-electric secondary energy is modeled to essentially maintain current trends in energy use, with only a modest degree of substitutability. A CES specification allows us to retain the composition of the fuels if the relative prices across inputs do not change appreciably. In order to allow for a rapid switch towards carbon-free non-electric energy, we sum the CES bundle to a perfectly substitutable backstop. The sectoral non-electric consumption supply of oil products satisfies the global demand $dNElec_{j\in\{I,O\}}$:

$$\begin{aligned} dNElec_{j\in\{I,RC\}} = {} & \overline{NElec}_{j\in\{I,RC\}}\left[\theta_{Liq}\left(\frac{dOilP_{j\in\{I,RC\}}}{\overline{OilP}_{j\in\{I,RC\}}}\right)^{1-\rho_N}+\theta_{Gas}\left(\frac{dGas_{j\in\{I,RC\}}}{\overline{Gas}_{j\in\{I,RC\}}}\right)^{1-\rho_N}+\theta_{Coal}\left(\frac{dCoal_{j\in\{I,RC\}}}{\overline{Coal}_{j\in\{I,RC\}}}\right)^{1-\rho_N}\right]^{\frac{1}{1-\rho_N}} \\ & +dBackstop_{j\in\{I,RC\}} \end{aligned}$$

Oil products can either be supplied by refined oil, called $refoil$, or by perfectly substitutable synthetic fuels obtained from liquefaction of coal, gas or biomass. The aggregate supply of oil products satisfies the global demand $\sum_{j\in\{I,RC\}} dOilP_j$: $\sum_{j\in\{I,O\}} dOilP_j(t) = \left[refoil(t)+coal(t)+gas(t)+bio(t)\right]\times NEloss$ where the fraction $NEloss$ accounts for transformation and distribution losses.

Nonrenewable Resource Supply

Each energy transformation process (e.g., coal to electricity) incurs specific investment and operation and maintenance costs. We assume that the investment cost function follows some endogenous reduction according to accumulated experience, i.e., through learning-by-doing (such as in Goulder and Mathai, 2000, van der Zwaan et al., 2002). The cost of investment[18] for plant et denoted by $invc_{et}$, is written as $invc_{et}(t)=\alpha_{et}\left[\int_0^t Elprod_{et}(s).ds\right]^{-lr_{et}}$ where α_{et} is a scale parameter and lr_{et} the learning rate of

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[18] Investment costs are annualized using a capital recovery factor $crf_{et}(t)=\frac{(1+\rho)^{lf_{et}}.\rho}{(1+\rho)^{lf_{et}}+1}$, lf_{et} being the life of the plant and ρ the discount rate.

technology et (see OECD, 2000, Goulder and Mathai, 2000). Operation and maintenance costs denoted by $O\&M_{et}$ are assumed to be constant over time.

The extraction cost of the nonrenewable resources, namely oil, gas, coal and uranium indexed by $i \in \{O,G,C,U\}$, are denoted by $c_{i\in\{O,C,G,U\}}$ and depend on the cumulative extraction at date t. The functional form for $c_{i\in\{O,C,G,U\}}$ is based on Nordhaus and Boyer (2000):

$c_{i\in\{O,C,G,U\}}(t) = \xi_1 + \xi_2\left[\left(\int_0^t x_i(s)ds\right)/\overline{X_i}\right]^{\xi_3}$ where $\overline{X_i}$ is the initial resource stock given by $\int_0^\infty x_i(s)ds \le \overline{X_i}$. The cost for biomass feedstock is assumed to be constant, suggesting that there is no opportunity cost of land. The levelized cost of generating electricity by plant et, defined by $EL\cos t_{et}$ is expressed in \$/unit of energy and consists of the fuel cost $c_{i\in\{O,C,G,U\}}$, the operation and maintenance cost $O\&M_{et}$ and the investment cost $invc_{et}$. It is computed using the formula

$El\cos t_{et} = \frac{c_{i|et}}{\eta_{et}} + \frac{\mathrm{O\&M}_{et} + invc_{et}}{Ldf_{et}}$ where η_{et} and Ldf_{et} are the efficiency and load factors for plant et. Similar calculations are done for non-electric costs, although not shown here.

Calibration Procedure for Demand

The exogenous projection for GDP is the same for all the models and is in line with the IPCC B2 scenario (Nakicenovic *et al.*, 2000), as depicted in Appendix Fig. B2. World GDP is \$333 trillion (in 2000 dollars) in 2100 and reaches \$464 trillion in 2150. The corresponding population projection is also shown in the Fig. B2. Sectoral world energy consumption in the base year D_j is extracted from IEA data (2002). The rate of GDP growth rate is assumed to be 3.2% initially, decreasing at 0.1% per annum and reproduces the IPCC B2 scenario mentioned above. Sectoral energy prices P_j are not available and thus need to be calibrated. The available data only provides sectoral prices for electricity, oil products, gas and coal at the country level. We thus use IEA price data (2001) to compute average prices that are weighted by country indigenous consumption for each fuel and sector. Base year world prices P_j are in turn computed as weighted averages of the various relevant fuel prices for each demand sector. Long run price and income elasticities for each sector are taken from Barker (1995). Finally, in order to reproduce the base year energy demands, the parameter A_j is obtained from $A_j = D_j(t_0)/\left[P_j(t_0)^{\alpha_j} Y(t_0)^{\beta_j}\right]$. All demand parameters are summarized in Appendix Table B1.

Energy Data

The parameters of the resource supply curves ξ_1, ξ_2 and ξ_3 as well as resource endowments $\overline{X_i}$ are shown in Table B2. These resources include known unconventional reserves (e.g., oil and gas in shales and tar sands). Atmospheric concentrations are computed using carbon emission rates from Nordhaus and Boyer (2000), after adjusting for the different time intervals in our model.[19] Cost data for electric and non-electric technologies is shown in Tables B3 and B4.

Nuclear Data

Aggregate estimated reserves of uranium ore, including those already discovered are estimated to be nearly 14.38 million tons (OECD, 2004).[20] The actual cumulative production of nuclear power since the technology was deployed now exceeds 34,000 TWh (1TWh=10^9 KWh). This implies that approximately one million tons of plutonium and 0.1 million tons of fissile waste have been produced, including discharged uranium and other fission by-products.[21] These values are used as initial stocks. Since reprocessed uranium is only used for mixed oxide fuels not considered in the paper, its initial stock is assumed to be zero.

LWR technology is modelled on the European Pressurized Reactor (EPR) with a capacity of 1450 MW, producing 11.46 TWh of power annually. The spent fuel discharge consists of 19.132 tons of uranium, 0.271 tons of plutonium, 0.0417 tons of minor actinides and 1.369 other tons of fission products (see Charpin, 2000). After reprocessing and cooling, each TWh of electrical energy generates 23 kg of plutonium and 120.5 kg of wastes.[22]

FBR technology is based on the European Fast Reactor (EPR) with a capacity of 1000 MW, producing 8.76 TWh of power. This plant requires 11.7 tons of uranium and 1.5 tons of plutonium annually. The spent fuel discharge consists of 10.4 tons of uranium, one ton of fission products and 0.3 tons of plutonium, which is recycled back into the plant.[23]

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[19] The algorithm is run on 5 year intervals, since reprocessing of the spent fuel takes approximately 5 years. Since Nordhaus and Boyer use 10 year intervals, we adjusted their emission rates to correspond to our 5 year intervals.

[20] Our estimates, computed independently, are similar to those developed by an interdisciplinary MIT (2003) study (16 million tonnes).

[21] During this period, $(1-\varepsilon)$ or 0.917 million tons of depleted uranium have been stockpiled (OECD, 2004).

[22] LWR waste production decreases with FBR operation because of reprocessing of spent fuels.

[23] Further details on the energy content of fissile material are available in tabular form from the authors and from

Long-run cost estimates for nuclear power are obtained from NEA (1994 and 2002). We have simplified the specification of the technology and regrouped some stages whose costs are low or which involve a simple transformation of products without any storage. The cost of reprocessing or storing joint products such as reprocessed uranium from LWR plants which can be used in FBR technology are suitably apportioned between the two technologies. For simplicity, we assume constant returns to scale technologies and unit costs that are fixed over time. It is likely that technological change and the costs of labor, capital and materials may alter relative costs over time. It is difficult to predict these changes *ex ante,* but we partly address this issue by applying across the board technology-induced cost reductions.

The unit cost of extraction of uranium oxide and its conversion to uranium hexafluoride is assumed to be $60/kg of uranium. The separation and enrichment stage involves processes that add significant value to the mineral.[24] The cost of enrichment is taken as $80/kg of uranium. The fuel fabrication stage also represents a significant part of the fuel cycle cost and depends largely on the type of reactor. It is assumed to be $250/kg for LWR fuels, and a high $2,500/kg for FBR fuels, partly because of additional safety measures associated with the handling of large amounts of plutonium. The unit cost of reprocessing spent fuel is assumed to be $700/kg for LWR and $2,000/kg for FBR.

Investment costs represent the largest fraction of total costs in electricity generation. They are assumed to be $1800/kW for LWR, and $2100/kW for FBR. The disposal cost of depleted uranium is taken as $3.5/kg. The cost of interim storage of plutonium is a high $1,000/kg, due to its toxicity. The cost of conditioning of the waste and long-term geological storage is assumed to depend on whether or not wastes are recycled. We use $400/kg for Models C and D and $100/kg for Models E and F. Table B5 provides a summary of the cost estimates.

Hore-Lacy (2003).

[24] Separation produces a large quantity of stockpiled depleted uranium. Recall that this stock is waste in a LWR operation, but is an important source of uranium for FBR technology.

Supplementary Appendix B. The Nuclear Model with Recycling of Materials

Introduction

Uranium is the main raw material used in the generation of nuclear power. Almost two thirds of the world's uranium reserves are found in four countries - Australia, Kazakhstan, Canada and South Africa.[25] In the Light Water Reactor (LWR), which is the most common technology used, mined uranium ore is enriched from 0.7% to 3.5%.[26] Uranium fissions to produce heat which is converted into steam that drives a turbine and produces electricity. The spent fuel contains most of the original uranium and some plutonium. This recovered uranium can be reprocessed, enriched and mixed with the plutonium in the spent fuel to produce a mixed oxide fuel that can be put into long term storage or reprocessed. We also consider a modern nuclear technology, the Fast Breeder Reactor (FBR), about 20 prototypes of which are in operation. These reactors are more efficient in using uranium. They use plutonium as base fuel but also produce it as waste. The FBR can extract approximately 60 times more energy from each ton of uranium than the conventional LWR. However, its higher capital costs and the present low price of uranium makes the FBR uneconomical.[27] About 434 nuclear reactors are in service globally, representing an installed production capacity of 351 Gigawatts (GW). Another 36 reactors are currently under construction.

Elements of the Model

The simplified nuclear model we use is briefly described here (NEA, 1994). Natural uranium is enriched for use in a LWR plant or used directly in a FBR plant. Production of nuclear power from LWR technology is assumed to be a linear function of the enriched uranium input. The enrichment process creates large quantities of depleted uranium, which cannot be used in the LWR but has economic value as an input in the FBR fuel mix. A key difference between the two technologies is the existence of joint products: several by-products from LWR production, the most important of which is plutonium, are used as inputs into FBR production. The LWR technology produces three different by-products: fissile waste which must be treated and stored, and plutonium and reprocessed uranium, both of which can be used in FBR reactors. These complementarities in material flows are shown in Fig. B1.

Consider a single deposit of low grade uranium ore starting at point A in the figure. This natural uranium could be enriched for use in a LWR plant or used directly without enrichment in a FBR facility. Define

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[25] These reserves are recoverable at uranium prices of up to $80/kg. Current prices are about $30/kg. At substantially higher prices, seawater could be tapped for large amounts of the metal.

[26] To facilitate comparison, weapons programs require uranium enrichment of over 90%.

[27] This low price is partly due to the availability of weapons grade uranium and plutonium from military stockpiles of the US and the former Soviet Union. This higher grade uranium is blended down to provide reactor fuel. It currently provides almost 15% of the world's annual uranium supply.

u_E^L as the instantaneous flow of natural uranium that is enriched and used in a LWR plant. Enriching the ore leads to the separation of uranium into enriched uranium (u_E^L) and depleted uranium (u_D^L). Let these ratios be ε and $1-\varepsilon$, respectively, with $0<\varepsilon<1$. Then $u_E^L = \varepsilon u_N^L$ and $u_D^L = (1-\varepsilon)u_N^L$. Let q^L be the instantaneous production of energy (electricity) from LWR technology. We assume that it is a linear function of enriched uranium $u_E^L = \alpha^L q^L$. The LWR technology produces three different by-products - fissile waste which cannot be re-used and must be stored; plutonium, and reprocessed uranium. The last two can be re-used in the FBR. The amount of plutonium produced by LWR technology is denoted by Pu^L and is assumed to be proportional to the instantaneous production rate q^L, i.e., $Pu^L = \beta^L q^L$. The amount of reprocessed uranium is similarly given by $u_R^L = \xi^L q^L$. The volume of wastes w^L generated by LWR technology is $w^L = \gamma^L q^L$, where $\alpha^L, \beta^L, \gamma^L$ and ξ^L are given positive coefficients.

Let q^F be the corresponding production of energy from FBR technology. Again, we assume this to be a linear function of natural, depleted or reprocessed uranium, denoted respectively by u_N^F, u_D^F and u_{Ri}^F, where the subscript i denotes input. For simplicity we assume that they are perfect substitutes so that $u_N^F + u_D^F + u_{Ri}^F = \alpha^F q^F$. This is shown by point B, where the stocks of natural, depleted and reprocessed uranium are merged into one. The unique feature of FBR technology is that it can reuse part of the plutonium produced. Therefore the choice of the breeding ratio, i.e., the input-output ratio of plutonium, denoted by μ^F is endogenous. Thus the input of plutonium is given by $Pu_i^F = \beta^F q^F$ and the output (denoted by subscript o) by $Pu_o^F = \mu^F \beta^F q^F$. The uranium and plutonium inputs in FBR must be used in fixed proportion k. Their complementarity is described by the relationship $\frac{u_N^F + u_D^F + u_{Ri}^F}{Pu_i^F} \equiv k = \frac{\alpha^F}{\beta^F}$.

The output of reprocessed uranium from FBR technology is denoted by u_{Ro}^F.[28] Its proportion is given by $u_{Ro}^F = \xi^F q^F$. Let w^F represent the amount of waste generated by the FBR technology. Then $w^F = \gamma^F q^F$. Again, $\alpha^F, \beta^F, \gamma^F$ are positive constants. In summary, FBR technology uses uranium (natural, depleted and reprocessed) and plutonium as inputs, and produces energy, reprocessed uranium, plutonium and waste fissile material.

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[28] The uranium input and output also need to be used in fixed proportions, satisfying the condition: $u_N^F(t)+u_D^F(t)+u_{Ri}^F(t) \equiv u_{Ro}^F(t)(\frac{\alpha^F}{\xi^F})$.

In summary, natural uranium is enriched before use in a LWR plant. This process increases the proportion of fissile uranium which sustains the chain reaction in a LWR reactor. The process of enrichment also generates large quantities of depleted (lower grade) uranium, which needs to be stockpiled, and has little economic value. However, this depleted uranium can be used in FBR technology, along with plutonium. Thus, the waste material from enrichment can be put to use in FBR reactors, producing yet more plutonium which can be used again.

Stock Dynamics

We consider five distinct stocks of resources: natural uranium (in the ground), depleted uranium, reprocessed uranium, stockpiled plutonium, and nuclear wastes. The stock of uranium ore in the ground, $U_N(t)$ is enriched and declines by the quantity extracted for LWR, $u_N^L(t)$ and FBR, $u_N^F(t)$ given by $\dot{U}_N(t) = u_N^L(t) - u_N^F(t)$. The stock of depleted uranium $U_D(t)$ is augmented by the depleted uranium which is rejected from the enrichment process $u_D^L(t) = (1-\varepsilon)u_N^L(t)$, and reduced by the extracted quantity to be used in FBR, $u_D^F(t)$ given by $\dot{U}_D(t) = (1-\varepsilon)u_N^L(t) - u_D^F(t)$. The stock of reprocessed uranium $U_R(t)$ is augmented by the reprocessed uranium $u_R^L(t)$ from LWR and $u_{Ro}^F(t)$ from FBR, and reduced by the quantity $u_{Ri}^F(t)$ to be used in FBR, and is given as $\dot{U}_R(t) = u_R^L(t) - u_{Ri}^F(t) + u_{Ro}^F(t)$. The stock of plutonium $Pu(t)$ is augmented by the quantity $\beta^L q^L(t)$ out of the LWR plant, minus the FBR input $\beta^F q^F$, and augmented by the plutonium created by FBR technology, $\mu^F \beta^F q^F$ with $\mu^F > 1$. Now define Δ as the time lag between the date at which the plutonium flow is extracted from the reactor and the date at which it is reintegrated into the plutonium stock for re-use, caused by the need to reduce the temperature of the mineral and other processing tasks. This is given by

$$\dot{Pu}(t) = Pu_o^F(t) - Pu_i^F(t) + Pu_o^F(t) = \beta^L q^L(t) - \beta^F q^F(t) + \beta^F \mu(t-\Delta) q^F(t-\Delta).$$

Finally, the flow of wastes from the two technologies, w^L and w^F are aggregated as follows: $\dot{W}(t) = w^L(t) + w^F(t)$. We assume zero radioactive decay of the nuclear waste because of the relatively short time horizon of the model.

Nuclear Cost Functions

Let m denote the average extraction cost of natural uranium. For the purpose of writing this model, we assume it is constant. In the empirical model, this cost increases with cumulative extraction as explained previously. The total extraction cost is $m\left(u_N^L + u_N^F\right)$. Let m^S be the unit enrichment (separation) cost of uranium used in LWR. Then total enrichment cost equals $m^S u_N^L$. This enriched uranium is packaged and assembled before use as an input in LWR production, at an average cost of m^L. Therefore, the total preparation cost of LWR uranium is $m^L u_E^L = m^L \varepsilon u_N^L$. The average cost of fuel reprocessing for LWR technology is denoted by m_R^L, so that the total cost is $m_R^L\left[\beta^L + \gamma^L + \xi^L\right]q^L$. Finally, the LWR reactor incurs an *in situ* operating cost of $v^L q^L$.

Let m_f^F and m_R^F denote the average preparation and reprocessing cost of FBR fuel, respectively. Then the total FBR fuel fabrication cost is $m_f^F\left[u_N^F + u_D^F + u_{Ri}^F + r_i^F\right]$ and the total fuel reprocessing cost is $m_R^F\left[\mu\beta^F + \gamma^F + \xi^F\right]q^F$. The operating cost of FBR technology is given by $v^F q^F$. Each unit of depleted uranium is stockpiled at an average annual cost of storage s_{U_D}, so that the total storage cost is $s_{U_D}.U_D$. Similarly, let the respective annual unit cost of storage for reprocessed uranium and plutonium be s_{U_R} and s_{Pu} so that the corresponding storage costs are $s_{U_R}U_R$ and $s_{Pu}Pu.$ Finally the annual unit cost of storage for reprocessed uranium is s_W so that the total cost is given by $s_W\left[\gamma^L q^L + \gamma^F q^F\right]$.

Optimization of the Nuclear Model

Production of nuclear energy is optimized by choosing the instantaneous amount of power generated by the two technologies, $q^L(t)$ and $q^F(t)$ and the breeding ratio $\mu^F(t)$, to maximize a social surplus function, net of total costs. Denote the instantaneous gross surplus as $S(t) = S(q^L(t) + q^F(t))$. With a constant social rate of discount δ, we have

$$\begin{aligned}
\underset{\{q^L(t)\},\{q^F(t)\},\{\mu^F(t)\}}{Max} \int_0^\infty \{S(q^L(t) + q^F(t)) - \quad & m\left[u_N^L(t) - u_{Nt}^F(t)\right] \quad - \quad \left[m^S + \varepsilon m_f^L\right]u_{Nt}^L(t) \\
- \quad & m_R^L\left[\beta^L + \gamma^L + \xi^L\right]q^L(t) - v^L q^L(t) \\
- \quad & m_f^F\left[u_N^F(t) + u_D^F(t) + u_{Ri}^F(t) + r_i^F(t)\right] \\
- \quad & m_R^F\left[\mu(t)\beta^F + \gamma^F + \xi^F\right]q^F(t) - v^F q^F(t) \\
- \quad & s_{U_D}U_D(t) - s_{U_R}U_R(t) - s_{Pu}.Pu(t) \\
- \quad & s_W\left[\gamma^L q^L(t) + \gamma^F q^F(t)\right]\} e^{-\delta t}dt
\end{aligned}$$

subject to

$$\dot{U}_N(t) = -u_N^L(t) - u_N^F(t), \qquad U_{N_0} > 0 \; given, \; U_N(t) \geq 0$$
$$\dot{U}_D(t) = -u_D^L(t) - u_D^F(t), \qquad U_{D_0} > 0 \; given, \; U_D(t) \geq 0$$
$$\dot{U}_R(t) = u_R^L(t) - u_{Ri}^F(t) + u_{Ro}^F(t), \qquad U_{R_0} > 0 \; given, \; U_R(t) \geq 0$$
$$\dot{P}u(t) = r_{ot}^L(t) - r_i^F(t) + \mu^F(t-\Delta) r_i^F(t-\Delta), \qquad P_{u_0} > 0 \; given, \; P_u(t) \geq 0$$
$$\dot{W}(t) = \gamma^L q^L(t) + \gamma^F q^F(t), \qquad W_0 > 0 \; given, \; W(t) \geq 0$$

$$\overline{\mu}^F - \mu^F(t) \geq 0 \quad \text{and} \quad \mu^F(t) - \underline{\mu}^F \geq 0,$$

$$q^C(t) \geq 0,$$
$$q^F(t) \geq 0,$$

$$u_N^L(t) = \varepsilon^{-1} \alpha^L q^L(t) \geq 0,$$
$$u_D^L(t) = (1-\varepsilon) \varepsilon^{-1} \alpha^L q^L(t) \geq 0,$$
$$r_{ot}^L(t) = \beta^L q^L(t) \geq 0, \qquad r_i^F(t) = \beta^F q^F(t) \geq 0,$$
$$u_{Rt}^L(t) = \xi^L q^L(t) \geq 0, \qquad u_{Ro}^F(t) = \xi^F q^F(t) \geq 0,$$

$$u_N^F(t) + u_D^F(t) + u_{Ri}^F(t) \equiv r_i^F(t).\frac{\alpha^F}{\beta^F} = \alpha^F q^F(t),$$
$$u_N^F(t) + u_D^F(t) + u_{Ri}^F(t) \equiv u_{Ro}^F(t) \left(\frac{\alpha^F}{\xi^F} \right).$$

The necessary conditions are available separately from the authors.

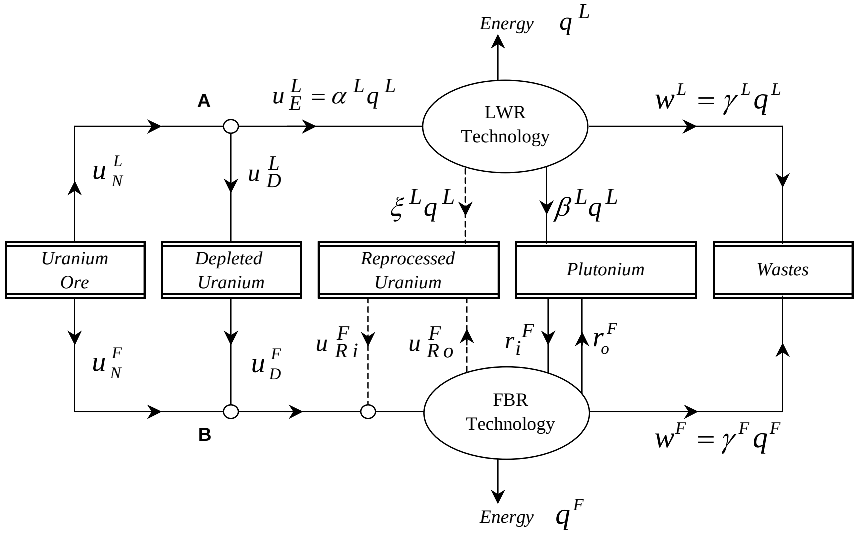

Fig. B1: Flow of Materials in the Nuclear Cycle

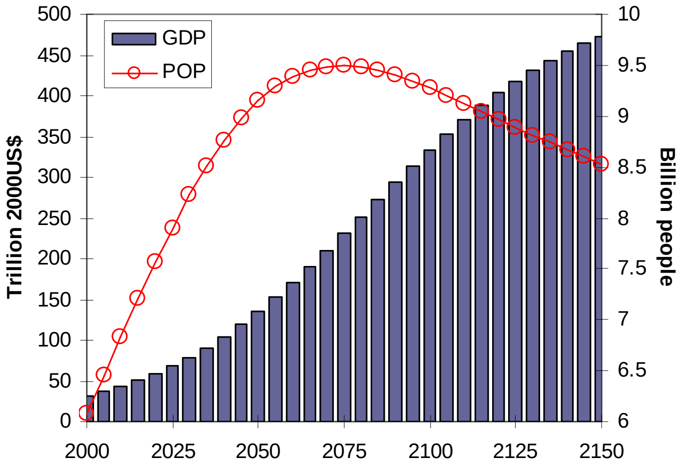

Fig. B2. Gross World Product (Left axis) and corresponding Population Projections (Right axis)

Table B1. Sectoral Demand Parameters and Base Year Calibration

	Energy Prices [(1)]	Energy consumption [(2)]	Weighted Prices	Price elasticity	Income elasticity	Constant parameters
	\$/GJ	EJ	\$/GJ	α_j	β_j	A_j
Transportation	18.01	71.06	18.01	-0.6	0.7	0.28598
Petroleum products	18.01	71.06				
Backstop	-	-				
Industry		81.41	7.07	-0.4	0.6	0.35622
Electricity	17.21	19.27				
Petroleum products	5.29	24.36				
Gas	4.32	20.56				
Coal	1.53	17.23				
Backstop	-	-				
Other		74.48	15.97	-0.5	0.5	1.67783
Electricity	27.21	25.52				
Petroleum products	11.79	20.11				
Gas	8.47	23.87				
Coal	11.24	4.98				
Backstop	-	-				

(1) Source: Retails prices for selected countries, IEA (2001).

(2) Source: Total final consumption from IEA (2002).

Table B2. Parameters for Resource Supply Functions(1)

		Oil	Gas	Coal	Uranium
Resource cost for base year (\$/GJ)	ξ_1	3.50	2.50	1.50	0.05
Parameter	ξ_2	100	100	20	0.5
Parameter	ξ_3	5	5	2	1.5
Resource endowment (EJ)	X_i	20013	24618	261466	6040

(1) Source: Adapted from Rogner (1995).

Table B3. Cost Data for Electric Technologies(1) ,(2)

	Lifetime	Efficiency	Load factor	Investment cost for base year	Investment floor cost	O&M cost	Energy cost for base year[1]	
	Years			\$/kW	\$/GJ	\$/GJ	\$/GJ	cents/kWh
Existing oil	20	0.30	0.65	1000	1000	2.59	19.11	6.88
Existing gas	20	0.33	0.65	1200	1200	2.16	15.23	5.48
Nat.Gas NGCC	20	0.56	0.65	450	350	0.44	6.91	2.49
Nat.Gas NGCC-CCS	20	0.47	0.65	1100	750	0.92	11.13	4.01
Existing coal	30	0.37	0.65	1050	1050	1.92	9.96	3.59
Coal IGCC	30	0.46	0.85	1500	1100	1.81	9.03	3.25
Coal IGCC-CCS	30	0.38	0.85	2100	1500	2.85	12.44	4.48
Biomass IGCC	30	0.40	0.75	2400	1100	1.59	16.21	5.84
Hydro	50	0.39	0.45	2850	2850	1.69	14.61	5.26
Wind	20	0.33	0.30	1200	500	1.26	12.43	4.47
Solar PV	20	0.20	0.30	4000	500	1.54	37.90	13.64

(1) Computed with a 5% discount rate. Initial extraction costs for gas, coal, and biomass are: \$3.5, \$2.5, \$1.5 and \$3 /GJ, respectively.

(2) Data source: NGCC and IGCC plants: IEA (2006). Others: IEA (2005).

Table B4. Cost data for non-electric technologies(1) ,(2)

	Lifetime	Efficiency	Load factor	Investment cost for base year	Investment floor cost	O&M cost	Energy cost for base year[1]
	Years			$/kW	$/GJ	$/GJ	$/GJ
Synthetic oil products							
Coal-to-liquids	30	0.65	0.80	2000	1000	3.22	11.24
Gas-to-liquids	30	0.53	0.90	1500	1000	2.59	10.9
Biomass-to-liquids	30	0.65	0.80	1150	750	3.22	11.35
Backstops							
Solar thermal-H2	20	0.30	0.35	4500	1000	1.1	33.82
Transp. - Fuel cell-H2	20	0.40	0.85	5500	3000	6.43	20.02
Industry - Fuel cell-H2	20	0.40	0.85	3500	500	8.13	18.72
Other - Fuel cell-H2	20	0.40	0.85	3500	500	6.43	17.02

(1) Computed using a 5% discount rate. Initial extraction costs are same as in Table B3.

(2) Data source: MIT (2007) and Williams et al. (2006) for synthetic fuel costs. Backstop costs are extracted from the Markal Model (see description in Barreto and Kypreos, (2004).

Table B5. Unit Costs for the Nuclear Technology (1)

Cost parameters		*LWR*	*FBR*
Conversion	m	5	5
Enrichment	m^S	80	-
Fuel Fabrication	m_f^L, m_f^F	250	2500
Investment	v^L, v^F	1800	2100
Processing	m_R^L, m_R^F	700	2,000
Depleted Uranium Storage	s_{U_D}	3.5	-
Reprocessed Uranium Storage	s_{U_R}	60	60
Plutonium Storage	s_{Pu}	1500	1500
Waste Disposal	s_W	400	100

(1) All costs in $/kg, except investment costs which are in $/kW.