NUCLEAR ENERGY AS RENEWABLE: AN ECONOMICAL AND SOCIAL ANALYSIS

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Introduction

Despite continuous economic and technological development in the field, energy sustainability remains one of the greatest challenges in the world today. Nuclear power, coal and natural gas are the only major parts of the base load of electricity, the sources that generate power continuously regardless of daily fluctuations in demand. Renewable energy sources contribute minimally to the base load of power because of their high cost, low density and poor stability. The only exception is hydropower, which is already fully developed in the U.S. and highly dependent on the geographical location with little potential for further advancement. Presently, the only practical alternative for ever-diminishing and environmentally costly fossil fuels is nuclear power. However, current government policies in the U.S. are very unfavorable for its development because of public opinion and political concerns. On April 14th 2011, the construction of the Yucca Mountain Nuclear Waste Repository, which had already cost 12 billion dollars [1], was officially terminated under the Obama Administration. This might have set back the opening of a new geologic repository by at least 20 years [2].

It is worth noting that the world's first electricity-generating nuclear power plant, Argonne National Laboratory’s Experimental Breeder Reactor I, was designed to validate the nuclear physics theory that suggested the possibility of a breeder reactor. A breeder reactor generates more fissile fuel than it consumes by converting fertile materials like uranium-238 or thorium-

232 into their fissile isotopes. The popularity of breeder reactors diminished soon after more uranium reserves were found in the 1960s, and new methods of uranium enrichment were invented to reduce fuel costs. However, the resurgence of breeder reactors would allow us to consider the possibility of classifying nuclear power as another source of renewable energy. Though federal support exists for the research and development of nuclear energy, favorable tax incentives drive current support for renewables to a level almost threes time higher than that for the nuclear industry, despite all renewables (excluding hydroelectric) producing only 1/8 as much power as nuclear as of 2007[3]. For electricity generation, the EIA concludes that solar energy is subsidized to about $24.34 per MWh, wind to $23.37 and "clean coal" to $29.81. On the other hand, nuclear power receives only $1.59 per MWh [4]. The current situation encourages us to think: what could happen to the economics of nuclear power if it were to be considered as a renewable resource?

This paper will first evaluate and demonstrate the validity of reclassifying nuclear power as a renewable energy source from a scientific perspective; then, a cost-benefit analysis of nuclear energy will be conducted for the private sector that applies current policy incentives for renewable energy to the nuclear industry. Next, the total cost of one kilowatt-hour of nuclear-generated electricity will be compared to that of coal. This includes the cost for the private sector adjusted after government subsidies, and externalities in the form of accidents and environmental impact. We discover that as of 2003, classifying nuclear energy as renewable would reduce the private cost of nuclear electricity production from $6.7/kWh to a competitive $4.6/kWh in comparison with $4.2/kWh for coal. On the other hand, the social cost of nuclear energy, which we mainly include accident costs and CO2 emission cost, is much smaller comparing to coal.

The purpose of this study is not to advocate for the reclassification of nuclear energy as renewable, but to provide a new perspective and to encourage both the general public and academia alike to evaluate its opinion of nuclear energy using scientific data and facts.

Classifying Nuclear Energy as Renewable

The definition of renewable energy varies a lot by different countries, states and agencies. In most cases, such a definition contains a description of renewable energy and a list of verified renewable energy types. For example, the EIA defines renewable energy as follows:

"Energy sources that are naturally replenishing but flow limited. They are virtually inexhaustible in duration but limited in the amount of energy that is available per unit of time. Renewable energy sources include: biomass, hydro, geothermal, solar, wind, ocean thermal, wave action and tidal action. [5]"

At present, most organizations do not recognize any kind of nuclear power as renewable energy with the exception of the American Petroleum Institute, which states, "fast-reaction [6] nuclear power fuel is considered renewable and sustainable[7]." In 2009, the state of Utah passed a bill titled *Economic Development Incentives for Alternative Energy Projects* that is aimed at renewable energy, and includes generation powered by nuclear fuel [8]. We will now evaluate the validity of classifying nuclear as renewable energy by the following criteria: *environmental cost, safety, and inexhaustibility*.

(1) Environmental Cost

When compared to fossil fuels, nuclear energy has the advantage of producing very little if any greenhouse gas. When considering renewable electricity-generating facilities of equal capacity, wind power requires 10 times more steel, 4 times more concrete, and 533 times more land than nuclear; solar power requires about 58 times the land with a much higher cost for the semiconducting materials in solar panels [9]. In addition, any commercial-scale wind or solar installation requires a companion reserve power plant of the same capacity fueled by a fossil-based energy source available on demand. The financial and environmental cost of such backup plants that address the intermittency issues of solar and wind power is rarely calculated [9].

(2) Safety

The biggest misconception about nuclear power is about its safety: when people hear radioactivity, they think of something that is very dangerous. In fact, nuclear reactions are nothing but the most common events in nature. All other kinds of renewable energy are also the result of nuclear reactions in the core of sun (solar, wind, hydropower) and in the core of earth (geothermal). Moreover, natural, large-scale nuclear reactors even exist on the surface of earth; a chain reactor is inside a mountain in Gabon, West Africa. Such natural reactors provide useful data on long-term storage of spent nuclear fuel, as well as some insights into possible improvements for man-made reactors. Breeder reactors, especially integral fast reactors (Till *et al. 2011*), can extract 100 times more energy from uranium ores than current commercial light water reactors by recycling and consuming almost all of the actinide. In this case, the only waste produced are the fission products whose radioactivity reduces to the natural level found in ores in 300 years rather than the 30000 years it takes for the spent fuels from light water reactors (Till *et al. 2011*). Fuel recycling was an important part of Fermi’s original nuclear plan to both increase energy efficiency and reduce waste, but the U.S. government banned it in 1974 as part of a non-proliferation policy. On the other hand, fuel recycling at a breeding ratio (recycled fuel/input fuel) that is higher than 1 for breeder reactors and lower than 1 but steadily increasing for light water reactors has been successfully tested and applied in countries such as France, India, Korea and China. Even without recycling, the amount of nuclear waste is very small in volume comparing to the huge amount of energy nuclear plants have provided. If all the used fuel from the past four decades of U.S. nuclear power were stacked together, it would cover a single football pitch only a few yards deep[9]. Current storage technologies have demonstrated the ability to contain radioisotopes for up to hundreds of years, but a long-term geologic repository is still in great and urgent need.

The general public has been frightened by high-profile nuclear accidents such the Three-Mile Island Accident in the U.S., the Chernobyl Accident in the USSR, and the recent Fukushima-Daiichi Accident in Japan. However, only the Chernobyl Accident, the result of multiple procedural violations, has caused any deaths thus far. The death rate per terawatt-hour is 15 for coal in the U.S., 168 for coal worldwide, 36 for oil, 4 for natural gas, 12 for biofuel, 0.44 for rooftop solar, 0.15 for wind, 0.1 for hydro in Europe, and finally 0.04 for nuclear[10]. Thus nuclear proves to be the safest energy in terms of death rate.

(3) Inexhaustibility

Without breeder reactors, fissile uranium is a non-renewable resource. Breeder reactors can turn fertile uranium, which is abundant on earth, into fissile uranium. A joint report by the Organization for Economic Co-operation and Development (OECD), the Nuclear Energy

Agency and the International Atomic Energy Agency in 2003 concluded that known conventional uranium resources (<$130/kg) are enough for 85 years and total conventional uranium resources (<$130/kg) are enough for 270 years with the current once-through light water cycle. With breeder reactors, total conventional uranium resources (<$130/kg) are enough for 8500 years[11]. At a cost of $300/kg, uranium can be extracted from seawater with current technology; the amount of total uranium reserve in seawater is estimated to be 4000 million tons compared with 14 million tons of total conventional uranium as of 2003[12]. It is worth noting that since fuel cost only amounts to a small fraction of nuclear energy's total cost per kWh, and raw uranium price also constitutes a small fraction of total fuel costs, such an increase on uranium prices wouldn't involve a very significant increase in the total cost per kWh produced. Furthermore, physicist Bernard Cohen claimed that seawater uranium is constantly replenished by rivers eroding the Earth's crust at a rate of 6500 tons per year, and the uranium in the crust is effectively inexhaustible (Cohen, 1983). Beyond uranium, breeder reactors can also use thorium as fuel. Thorium is much more abundant on earth and can be used to breed fissile uranium-233.

Therefore, we believe nuclear power is a clean, safe, and inexhaustible kind of renewable energy. Breeder reactors are critical in our discussion. Even though they are next-generation technology for commercial use with a very high cost at present, their scientific and engineering success has been demonstrated by Experimental Breeder Reactor II in the U.S. and other research and development efforts in the world. As we continue to develop nuclear energy, the price of uranium will increase to the point where unconventional methods of extracting uranium become attractive, and breeder reactors become profitable for electricity generation. This will enable the replenishment of fissile uranium by breeding fertile uranium. Thus, we have come to a conclusion that nuclear fuels such as uranium and thorium are renewable sources of energy and the power generated by the traditional light water reactors *and* breeder reactors could be considered as a kind of renewable energy. As former President George W. Bush once proposed, nuclear energy is clean and renewable [13].

Current Renewable Energy Policy

Current renewable energies enjoy many incentives from the United States government for their production and consumption. If nuclear power were to be re-classified as renewable, some of these incentives may become available for it, reducing its effective cost. These would primarily help with the large fixed cost required to build nuclear facilities, as this is the main obstacle for a corporate entity entering the nuclear business.

The criteria used for selection of potentially applicable policies uses these rules: first, the policy in question must apply to at least one established renewable energy sector already. Secondly, there must be appropriate reason to believe this policy would feasibly exist for nuclear energy. For instance, a policy on the residential side that awards a tax credit to households that invest in domestic production of renewable energy may be relevant when applied to wind or solar power (i.e. a personal windmill on a farm or solar panels on roofs), but highly impractical when it comes to nuclear power. This section will address applicable policies and programs.

The Business Energy Investment Tax Credit (ITC)[14] applies to commercial, industrial, utility, and agricultural sectors; it is designed to incentivize investment in facilities that produce renewable energy such as solar and wind. This policy subtracts thirty percent of a corporation’s expenditures on these new facilities and associated equipment from the taxes it must pay. There is no maximum limit on this credit. In 2009 a restriction was removed on this policy that prevented the received tax credit from being used in other renewable energy projects eligible for the same credit. Thus, corporations may now invest the credit in other renewable projects that are also eligible under ITC.

A similar program is the Renewable Energy Production tax credit (PTC)[15]. This program provides a tax credit for the *production* of renewable energy. For wind, geothermal, and closed-loop biomass, the policy subtracts 2.2 cents per kilowatt-hour of energy produced from overall corporate taxes. The award generally applies for the first ten years of production. Businesses eligible for the PTC are now allowed to now choose *between* the ITC mentioned above and the PTC when building new facilities; this is a result of the American Recovery and Reinvestment Act of 2009.

The United States Department of Energy Loan Guarantee Program [16] already has a large impact on the nuclear industry [17]. This program promises that the United States Government will assume the debt of a borrowing party if that party defaults on a loan. This currently applies to nuclear energy already, as well as a very broad range of renewable technologies. The policy is intended to promote commercial use of improved technologies for energy production. Because of this, the technology must not be currently widely used in a commercial setting to be eligible. For example, a nuclear reactor that is shown to be more efficient than reactors currently producing energy at a commercial scale would be eligible for this program. This ensures that the technology must show improvement from current technologies by either an innovation, improved efficiency, or a new application. While this does not impact cost directly, it helps offset the risk of the massive investment required to build an operational nuclear facility. There is no specified maximum incentive for this program.

The Modified Accelerated Cost-Recovery System (MACRS)[18] provides corporate depreciation to those investing in property for renewable energy production. For various class lives ranging from three to fifty years, businesses are able to deduct the cost of the property divided over its class life from taxes, retaining a percentage of this deduction in tax savings. The depreciation for a property uses a cost calculated *after* tax benefits (for example, the ITC); *one-half* of any tax credit received is subtracted from the overall basis. There is also a possibility for bonus depreciation, which allows property with a lifespan of twenty years or less to deduct fifty percent of the eligible basis in the first year, with the other fifty percent being depreciated normally in the following years. Most property for renewable energies including solar and wind is currently categorized under a five-year class life; though the provisions allow for class lives of up to fifty years, it is hard to say whether nuclear energy would qualify for this program in its current state. While some power facilities may have a lifespan of fifty years now, we would hope to see that the lifespan of future facilities (and some currently operating ones) would exceed fifty years; it is possible that this policy would be updated to include longer class lives if nuclear energy were added to it. Under current legislation, nuclear energy plants would not be eligible for any additional bonus depreciation, though this may change if the government feels the need to increase incentive for nuclear energy production.

A final point to address is that the licensing process for new nuclear power plants through the United States Nuclear Regulatory Commission (NRC) is quite complex[19], and poses a large obstacle to new ventures into nuclear energy. Understandably, application reviews are very detailed, and include analysis of the design, safety, building site, and environmental impact of a plant, among many other things. There have been large improvements made to the process in the last twenty years, reducing the time it takes to review an application from sometimes over twelve years to three and a half[20]. Still, there is more room still for improvement, especially that which could be brought about by the reclassification of nuclear energy as renewable. Taking advantage of the potential benefits and incentives described above, industry could work at a faster pace to improve the safety and efficiency of nuclear technology so it more easily meets the requirements of the NRC, making it easier for them to review applications in a timely manner.

Private Cost

(1) Discussion of Method

The primary aim of this section is to provide an estimated levelized cost of nuclear-generated electricity for the private sector if it were to be classified as a renewable energy source. The first step is to develop a “no-policy” base model and the second step is to change input parameters such as debt ratio and equity return rate, and add a tax credit under the additional beneficial policies. This section uses the merchant cash flow model from the MIT study written by a faculty group led by Prof. John Deutch and Prof. Enrnest Moniz as a guideline to estimate the private cost.

Though nuclear power can be used to generate electricity very efficiently, the construction of new plants was not evenly processed throughout the past 10 years largely due to safety concerns. The level of current progress is varied in different parts of the world. As it is stated in the MIT study (2009), “there are only few firm commitments outside of Asia, in particular China, India, and Korea, to construction projects at this time and no new nuclear units have started constructions in the U.S since 2003” (Beckjord *et al.*). On the other hand, due to the Fukushima-Daiichi nuclear disaster, all of the nuclear reactors in Japan have been shut down in 2012(Schneider *et al.*). It is hard to predict whether this recent incident has affected financial risks for upcoming nuclear plant projects and how much should this be factored into the construction of U.S. nuclear plants due to different geographic locations. Instead of dealing with the idea of accidents in the calculation of financial risks, we would like to incorporate it in the social cost section following this one.

Before we proceed to the actual calculation of private costs, it is important to identify three major economic factors that determine competitiveness of the nuclear energy. The first two barriers are those of capital costs, and those of operation and maintenance (O&M) costs. Costs of machines and safety protections are much higher in the building nuclear power plants than coal plants. On the other hand, as Prof. George Tolley pointed out in his study “capital costs between a first new nuclear plant and some nth plant of the same design can be critically important to eventual commercial viability” (Tolley *et al.*, 2004). In other words, the real overnight capital cost can decrease as engineers and construction workers learn the design of plants along the way. Once the nuclear plant is built, the sunk cost should not interfere with decision-making later on. The marginal cost of producing one more unit of electricity is in fact cheaper under this condition. Furthermore, the third factor is that a nuclear plant is considered to be a much riskier investment than a coal plant due to uncertainties and risks such as the difficulty of obtaining licenses. In the “no-policy” base case, because financial institutions are reluctant to lend money to risky projects, the building of a nuclear plant needs to lean more on equity financing, and expected return to equity investors is higher for nuclear plants than for coal plants. In the base case, a debt/equity ratio of 50% is needed for nuclear instead of 60% for coal, and the rate of return for the equity investment of 15% is needed for nuclear, higher than the equity return rate of 12% for coal and the debt interest rate of 8%, making nuclear less attractive than coal. However, uncertainty involved in the investment can be mitigated and internalized by the government instead of individual consumers and private investors. The supportive government policies and the tax credit benefits in the renewable case discussed above help to increase the confidence of investors in nuclear energy, and thus eliminate the risk premium so that the requirements for the debt ratio can be increased and those for the equity return rate can be decreased to the same level as the coal plant. In other words, a nuclear plant in the renewable case should encourage other private investors to enter the market and make nuclear power plants available. Assistance from the government does not only help lower the capital cost but also lowers the financial risks.

In sum, we attempt to compare the levelized cost of electricity generated by a nuclear plant to that of a coal plant *with and without* the help of government policy incentives. The assumptions we make to calculate the levelized price of electricity are that the plants must cover operation expense, pay back debt in a 10-year term and provide a specified internal rate of return to the equity investors. Moreover, we assume there is one nuclear plant and one coal plant of equal capacity, each with a life of 40 years in our comparison scenarios. In the renewable case, since nuclear energy is classified as renewable energy we treat the nuclear plant and coal plant with the same financial terms and a PTC tax credit is given for each kWh of electricity produced by the nuclear plant. The benefit of reclassifying nuclear as renewable energy is a net reduction of cost due to increased confidence and a shift of cost to the government by tax credit.

(2) Dataset

The capital and fuel cost data sources are from EIA – Annual Energy Outlook 2003, and the input of risk parameters is adjusted according to current government policies. The Annual Energy Outlook is an ongoing data collection and analysis started in 1979 by the U.S. government and industrial agencies. The following Table 1 is a summary of the input parameters for the base case. The debt ratio and equity return rate will be changed to the same level as the coal plant in the renewable case for comparison, and a tax credit of 2.2cent/kWh or 1.1cent/kWh will be added.

Base Case Input Parameters: (2003 Data)	Nuclear	Coal
Inflation Rate	3%	3%
Debt Interest Rate	8%	8%
Debt Term (year)	10	10
Debt Fraction	50%	60%
Expected Return to Equity Investor	15%	12%

Net Capacity (MWe)	1000	1000
Capacity Factor	85%	85%
Plant Life (year)	40	40
Heat Rate (BTU/kWh)	10400	9300
Overnight Cost ($/kWe)	2000	1300
Construction Period (year)	5	4
Depreciation Schedule (year)	15	15
Real Fuel Escalation	0.5%	0.5%
Fuel ($/mmBTU)	0.47	1.2
Waste Fund ($/kWh)	0.001	0
Fixed O&M($/kWe/year)	63	23
Variable O&M ($/kWh)	0.00047	0.00338
O&M Real Escalation Rate	1%	1%
Decommissioning ($ Million)	350	0
Incremental Capital ($/kWe/year)	20	15
Carbon Intensity (kg-C/mmBTU)	0	25.8
Tax Rate	38%	38%

Table 1

(3) Comparison and Result

Table 2 below summarizes results in all cases.

Result in All Cases	
Different Cases	Levelized Cost of Electricity ($2003/kWh)
Nuclear Base Case:	6.7
Equal Financial Terms as Coal:	6.1
Tax Credit 1.1 cent/kWh:	5
Tax Credit 2.2 cent/kWh:	4.9
Equal Financial Terms and Tax Credit 1.1 cent/kWh	4.7
Equal Financial Terms and Tax Credit 2.2 cent/kWh	4.6
Coal Base Case:	4.2

Table 2

In the base case without government assistance, the levelized price of electricity is 6.7cent/kWh and 4.2cent/kWh for nuclear plant and coal plant respectively. The nuclear plant is definitively less competitive than the coal one. When adding in a boosted confidence due to risk offset from recognizing nuclear as renewable energy, the private cost of nuclear electricity is reduced to 6.1cent/kWh. If a tax credit of 1.1cent/kWh is also added, the private cost of nuclear electricity if further reduced to 4.7cent/kWh. If a tax credit of 2.2cent/kWh is added instead, the private cost of nuclear electricity is reduced to 4.6cent/kWh. As we see, the levelized price of electricity for nuclear plant displays a downward trend under the government’s beneficial policy. The private cost of nuclear electricity becomes economically competitive with coal when these policies are applied. It is worth noting that in the renewable case, the effective government cost for these policy incentives can be estimated by the difference between the nuclear electricity cost with only the risk premium offset, and the cost that also includes the tax credit, i.e. 6.1-4.6=1.5cent/kWh. The reduction of cost due to risk premium offset only (6.7-6.1=0.5cent/kWh) is a net gain at no party's cost.

Social Cost

In the previous part, we saw that nuclear energy would be feasible if granted subsidies from the government similar to those granted to renewable energy. But another important question still remains: why should the government subsidize nuclear energy? A justification can be given by showing that the total cost of nuclear energy, which consists of the cost in the private sector adjusted by government subsidies, is comparable with the private cost of coal. As we have already calculated the subsidy-adjusted cost in the private sector, in this section we will calculate the social cost of nuclear energy and the coal, which comes from CO2 emissions, and the possibility of accidents.

(1) Social Cost From CO2 Emission

One of the main pieces that contributes to the social cost of electricity generation is CO2 emission. To calculate this part of the social cost, we can use the equation:

$$C_i = \mu_i \cdot V$$

Here, C_i is the social cost due to the CO2 emission of a specific kind of energy, μ_i is the carbon emission rate (tC/kwh) of electricity generation, and V is the social cost of carbon emission

(USD/tC). The way to calculate V will be discussed in the following paragraphs.

By definition, the social cost of carbon (SCC) is the monetary value of damage done by emitting one more tonne of carbon at some point of time. In choosing the reference point for time to be the current period, we should be conscious that this marginal damage cost would rise in future periods, because greenhouse gases accumulate in the atmosphere.

The general way to calculate the total damage,, from the emission of 1 ton of greenhouse gas is to add up the present value of all future incremental damages, $\frac{\partial D_t}{\partial E_t}$. Denoting time as t, we have the equation (Pearce, 2003):

$$V = \sum_{t=0}^{T} \frac{\partial D_t}{\partial E_t} \cdot (1+s)^{-t}$$

In this equation, s is the social discounting rate; D_t and E_t are respectively the damage and emission of greenhouse gas at time t. From this equation, we can see that the value of total damage highly depends on the value of the social discount rate, which will be shown later.

Based on the above equation, there are various models that calculate the SCC with different levels of sophistication. As Pearce (2003) and Bickel (2005) suggest, we adopt the model titled The Climate Framework for Uncertainty, Negotiation and Distribution (FUND), which has been developed by Richard Tol since 1995 and is widely used by different projects such as EU Integrated Projects. The latest FUND, version 3.7, was updated in October 2012, while most published papers are using data generated by version 2.6, which was released in 2004. To get more reliable data, we examined the source code of FUND 3.7 from http://www.fund-model.org/

and rewrote it to calculate the SCC in 2012.

FUND is a sophisticated and well-developed model. Essentially it consists of a set of exogenous scenarios and endogenous perturbations, specified for sixteen major world regions. The model runs from the year 1950 to 3000, with each period step being one year. The essential linkages in the model that calculate the damage caused by greenhouse gasses consist of five parts. The first three are: a link from emission of greenhouse gasses to their total concentration in the atmosphere, a link from this concentration to the temperature change, and a link from the temperature change to the resulting sea level change. The fourth linkage is from the changes in temperature and sea level to their impacts, which are in agriculture, forestry, water resources, energy consumption, loss of land, ecosystems, human health and extreme weather. And for each part of these four linkages, it adopts the appropriate model in the corresponding area discussed in FUND's documentation [21]. The final linkage in FUND 3.7 is equity weighting. As we know 1$ damage to a poor person should be greater than that to a rich one, so to get the real damage of global warming to the world we should use equity weighting functions to correct the unweight value. FUND uses a utilitarian social welfare function to weight the social cost, which is expressed in equation:

$$D_{world} = \sum D_i \cdot \left[\frac{\overline{Y}}{Y_i}\right]^{\varepsilon}$$

And D_i here is the damage in each area; $\overline{Y}$ is the average per-capita income of the world, and Y_i is the average per-capita income in one of those sixteen regions. And ε here is a factor that evaluates how different 1$ damage to poor people would be from that to rich people. We choose ε = 1 here, which is a moderate and default value in FUND 3.7.

With the this model, we use the data that FUND provided [22] and get the value of the SCC with different social discount rates:

Social Discount Rate	Social Cost of Carbon (USD/tC) [base year 2003]
s=1%	60
s=2%	16
s=3%	3

From this table, we can see that the SCC varies a lot with the value of the social discount rate we choose. And the real value of social discount rate is highly debatable, but generally accepted as between 1% and 3%. Besides this, we should also be aware of other assumptions and limitations of this model. The first assumption of this model is that after year 2300, all countries in the world are steady states, which mean that their population and GDP do not grow any more. Another important assumption for this model is that the social discount rate is constant. There are some works suggest that the discount rate for long term issues such as global warming decline with time (Weitzman, 1998; Gollier, 2003), and the SCC with a constant discount rate should be multiplied by a factor from 1.07 to 1.95(Pearce, 2003).

With the value of the social cost of carbon, we can calculate the social cost of each kind of electricity by multiplying the SCC each carbon emission rate. According to data from PIA, we know that in 2003 the CO2 emission rate of coal power plant is 916g CO2/kWh while that of a nuclear power plant is 6g CO2/kWh, which are 249.02g C/kWh and 1.63 C/kWh correspondingly. Thus we get the data below:

Social discount rate	Social cost of coal electricity (cent/kwh)[base year 2003]	Social cost of coal electricity (cent/kwh)[base year 2003]
s=1%	1.492	0.009
s=2%	0.402	0.002
s=3%	0.075	0.0004

And from the table above, we can see that nuclear energy has social benefit of 1.5 cent/kwh in reducing the CO2 emission.

(2) Social Cost of Accidents

Nuclear energy is perceived as unsafe because of a potential nuclear accident's devastating effect on human health and society. The Three Mile Island, Chernobyl reactors, and Fukushima accidents affected people deeply. Thus the social cost of nuclear accidents also should be taken into consideration when calculating the total cost of nuclear energy.

There is a set of risk assessment methods generally applied to this issue. The usual approach is to calculate the expected value of various accidents by multiplying monetary consequences by accident probabilities. However, it is important to integrate risk aversion perception within the calculation (Eeckhoudt *et al*., 2000). We will take advantage of a nuclear social cost calculation model used in France (Eeckhoudt *et al*., 2000) to analyze this cost in the United States. There are three steps in calculating the social cost of nuclear accidents: calculation of the expected total cost of an accident, calculation of the social cost of a nuclear accident per unit of electricity generated, and inclusion of a risk aversion factor.

The ExternE project was implemented in 1991 to assess the social cost of various fuel cycles in the production of electricity in the European Commission (Bickel and Friedrich, 2005). We will make some similar assumptions in our study. Different from other accidents, nuclear accidents are characterized by potential and differentiated influences in a local area and in the whole country. In our paper we define a local area to be within 50 miles of a nuclear power plant in the United States, and the region to be the whole United States. In the U.S., it's estimated that 116 million people are in a local area (i.e. within 50 miles of a nuclear power plant) and the remaining 199 million are in the region [23]. The annual U.S. nuclear electricity production is estimated to be 764 TWh [24]. The life value is estimated at $1 million/person [25], non-fatal effects compensation is estimated at $0.25 million/person. Other main social costs of a nuclear accident include the food-ban cost, evacuation and relocation cost, and indirect costs. Categories and assumptions of these costs are based on the model used in Eeckhoudt's paper (Eeckhoudt *et al,* 2000). We calculated the expected radio-induced health effects (Table 1) and their monetary consequences based on the COSYMA model, which is used in most major studies of nuclear accident cost estimation (Proult and Desaigues, 1993). The total cost is estimated to be $1.56*10^6$ million USD (Table 2).

Table 1. Number of expected fatal and non-fatal effects

Category	Area	
	Local (million)	Regional (million)

Number of fatal cancers	2.9e-02	1.11e-02
Number of severe hereditary effects	5.8e-03	2.22e-03
Number of non-fatal cancers	5.68e-02	2.19e-02
Number of early diseases	1.16e-04	4.45e-05
Total number of fatal effects	3.48e-02	1.34e-02
Total number of non-fatal effects	5.70e-02	2.19e-02

Table 2. Total cost of the nuclear accidents (ST21 Scenario applied to U.S.)

Cost category	Local costs (MUSD)	Regional costs (MUSD)	Total cost (MUSD)
Food-bans	1.91e+04	2.15e+04	4.06e+04
Evacuation and relocation	1.16e+06	0	1.16e+06
Fatal effects	3.48e+04	1.337e+04	4.82e+04
Non-fatal effects	1.23e-04	2.76e-05	1.50e-04
Indirect costs	3.03e+05	8.72e+03	3.12e+05
Total	1.52e+06	4.36e+04	1.56e+06

The risk aversion effect was calculated by a multiplying factor that captured people’s additional loss in utility from risk-aversion in the event of an accident. Let’s consider a risk situation with probabilities (p_1,p_2… p_N) and associated fractions of lost wealth (X_1, X_2… X_N). MA is the maximum fraction of wealth that a risk-averse individual is willing to pay to avoid a nuclear accident, and MN is an individual’s willingness to pay when he/she is risk-neutral. In order to take risk aversion into account, the initial social cost should be multiplied by the following multiplying factor (Eeckhoudt et al, 2000):

$$\frac{M_A}{M_N} = \frac{1 - \left[\sum_{i=1}^{N} p_i (1 - X_i)^{\beta}\right]^{1}}{\sum_{i=1}^{N} p_i X_i}$$

Past empirical studies estimate that the relative individual risk aversion coefficient is between 0.5-2.5. The higher the risk aversion coefficient is, the higher the additional loss in utility of a nuclear accident for the population is. To take into account people's impression of the devastating effect of nuclear accidents, we propose to choose a value of 2 for the relative risk aversion coefficient. The corresponding multiplying factor, which is the aggregate social effect of individual risk-aversion, equals to 20. With risk-aversion taken into account, the final formula for calculating social cost of nuclear accidents in the U.S. with respect to per-unit electricity generated is:

$$\text{External Cost} = \frac{\text{total cost of accident} \times \text{probability of occurence} \times \text{multiplying factor}}{\text{annual nuclear electricity production}}$$

The result is

$$\frac{1.56 \times 10^{6} \times 10^{-6} \times 20}{764 \times 10^{9}\text{kWh}} = 4.09 \times 10^{-5}\text{mUSD/kWh}$$

Comparison of the Social Cost of Nuclear Accidents with Coal

To compare with this result, the social cost of accidents in coal mining is also estimated. The main social cost of coal accidents will of course be death. Since things such as food-bans, evacuation, and relocation costs in the case of coal mining is relatively low, we include them in the indirect cost of coal accidents, which we assume to be 25% of the direct cost. Thus the basic formula for calculating social cost of coal accidents in the U.S.is:

$$\frac{\text{Annual death caused by coal accidents} \times \text{ Life value } + \text{ Indirect cost of coal accidents}}{\text{Annual coal electricity production}}$$

To calculate this, we average the number of deaths caused by coal accidents in the U.S. in the last ten years and multiply by the standard life value according to department of labor [26]. Our estimated total coal accident social cost thus is equal to [27]:

$$\frac{33 \times 10^{6} \times (1 + 0.25)}{1973 \times 10^{9}\mathrm{kWh}} = 1.27 \times 10^{-5}\mathrm{USD/kWh}$$

The estimated total social cost of coal accidents is much larger than that of nuclear (4.09*10-5 mUSD/kWh). This result is consistent with ExternE 's study of accident costs for nuclear and coal, which predicted that the expected social cost for nuclear accidents are much smaller than that of coal (Bickel et al, 2005).

To conclude on the social cost, nuclear energy has significantly smaller costs in terms of accidents and CO2 emissions when compared to those of coal. Thus from a cost-benefit analysis point of view, the use of nuclear energy seems to have an external benefit to society.

Topics for Future Discussion

The cost-benefit analysis framework we use in this model has its limit in treating problems related to nuclear proliferation and civil liberty damage. We thus pose the problems here for future discussions.

The safety of nuclear power plants containing concentrated nuclear fuel that can be used to make atomic bomb is a great concern for both the general public and the government. While the proliferation risk for one nuclear power plant is very small, the safety concern for large-scale application of it is legitimate. A related problem is damage to civil liberty. If nuclear plants were to be well-protected, strict daily checks of nuclear reactor workers, deployment of secret polices, and close supervision of nuclear plants' surrounding zones would be implemented. The large-scale implementation of these measures will impose a considerable cost on civil liberty.

The cost-benefit analysis framework has a limited ability to treat these problems because their consequences are hardly quantifiable. Take the example of highly concentrated nuclear materials being stolen by a nuclear-ambitious country. It is impossible to quantify how much damage the theft cost since the event could result in no effect or an extreme effect. Similarly, the cost of more strict safety measures on civil liberty is also non-quantifiable.

A possible solution for mitigating public concern for nuclear safety is to develop more advanced safety technology that reduces potential risk of nuclear proliferation to a minimum level (Pearce 1979). Such technology should ideally differentiate the nuclear fuel for electricity generation and for atomic weapon so that electricity level nuclear materials cannot be made into explosives. Another solution is to contain the more powerful fast breeder reactors in certainly well protected region and then supply their breeded fissile materials to light water reactors in other regions so that the proliferation risk to make weapon quality nuclear fuel is reduced. However, the prospect of developing such technology is also non-quantifiable thus unable to be treated by cost-benefit analysis framework.

Conclusion

This paper discussed the prospect of treating nuclear energy as a renewable energy. Judging from the standard of environmental cost, safety, and inexhaustibility, we argue nuclear energy could be qualified as a renewable energy. We then analyze this claim with a cost-benefit analysis model. The results show that nuclear energy would be both privately viable and socially optimal if classified as renewable energy. The private cost of nuclear energy is comparable to coal with government subsidies; further, its social cost is far smaller. It is also worth noticing that the government cost for the subsidies (1.5cent/kWh) is identical to the difference in social cost between coal-generated and nuclear-generated electricity. In conclusion, we argue that the classification of nuclear energy as a renewable is a scientifically valid, economically viable, and socially optimal option.

However, our cost-benefit analysis based model also has its limit in treating problems of nuclear proliferation and damage to civil liberties that might have huge potential consequences. We pose these problems for future discussions.

[1]: Northey, Hannah. "GAO: Death of Yucca Mountain Caused by Political Maneuvering." *New York Times*. May 10, 2011 < http://www.nytimes.com/gwire/2011/05/10/10greenwire-gao-death-of-yucca-mountain-caused-by-politica-36298.html >

[2]: United State Government Accountability Office. "Effects of a Termination of the Yucca Mountain Repository Program and Lessons Learned." April 2011 <http://www.gao.gov/new.items/d11229.pdf>

[3]: U.S. Energy Information Administration. "Federal Financial Interventions and Subsidies in Energy Markets 2007." < http://www.eia.gov/oiaf/servicerpt/subsidy2/pdf/execsum.pdf>

[4]: Wall Street Journal. "Wind ($23.37) v. Gas (25 Cents)." May 12 2008

<http://online.wsj.com/article/SB121055427930584069.html>

[5]: U.S. EIA. <http://www.eia.gov/tools/glossary/index.cfm>

[6]: i.e. fast breeder reactors

[7]: The American Petroleum Institute. <http://www.api.org/oil-and-natural-gas-overview/classroom-tools/classroom-curricula/key-characteristics-nonrenewable-energy-resources.aspx>

[8]: Utah House Bill 430, Session 198. <http://le.utah.gov/~2009/htmdoc/hbillhtm/HB0430.htm>

[9]: Blomquist, Roger. “Is Nuclear Energy Clean?” Critical Materials for Green Energy, September 2012, p40-42

[10] Godin, Seth. “Deaths per TWh by Energy Source.” *The Next Big Future*. <http://nextbigfuture.com/2011/03/deaths-per-twh-by-energy-source.html>

[11] OECD World Nuclear Agency and International Atomic Energy Agency. "Uranium Resources 2003: Resources, Production and Demand", p67.

[12]: OECD World Nuclear Agency and International Atomic Energy Agency. "Uranium Resources 2003: Resources, Production and Demand", p22.

[13]: Falka, John J.. “Bush Will Push Nuclear Power As Clean, 'Renewable'.” Wall Street Journal. Jan 12 2005 < http://online.wsj.com/article/0,,SB110549132459323561,00.html>

[14]: Database of State Incentives for Renewable Energy. “ITC” http://www.dsireusa.org/incentives/incentive.cfm?Incentive_Code=US02F&re=1&ee=1

[15]: Database of State Incentives for Renewable Energy. “PTC” http://www.dsireusa.org/incentives/incentive.cfm?Incentive_Code=US13F&re=1&ee=1

[16]: Database of State Incentives for Renewable Energy. “MACRS”

http://www.dsireusa.org/incentives/incentive.cfm?Incentive_Code=US06F&re=1&ee=1

[17]: Database of State Incentives for Renewable Energy. “U.S. Department of Energy Loan Guarantee Program” http://www.dsireusa.org/incentives/incentive.cfm?Incentive_Code=US48F&re=1&ee=1

[18]: U.S. Department of Energy. “About the Section 1703 Loan Program” https://lpo.energy.gov/?page_id=39

[19]: Nuclear Regulatory Comission. “New Reactor Licensing Process” http://video.nrc.gov/MediaPlayer.php?view_id=2&clip_id=121

[20]: Nuclear Energy Institute. “Licensing New Nuclear Power Plants” http://www.nei.org/resourcesandstats/documentlibrary/newplants/factsheet/licensingnewnuclearpowerplants/

[21]: Anthoff, David and Tol, S. J. Richard. 2012.“The Climate Framework for Uncertainty, Negotiation and Distribution (FUND), Version 3.6”. Web. 5 Dec 2012. <http://www.fund-model.org/versions/>

[22]: Anthoff, David and Tol, S. J. Richard. 2012.“The Climate Framework for Uncertainty, Negotiation and Distribution (FUND), Tables, Version 3.6”. Web. 5 Dec 2012. <http://www.fund-model.org/versions/>

[23]: The figure is acquired according to a study reported by NBC news at http://www.msnbc.msn.com/id/42555888/ns/us_news-life/t/nuclear-neighbors-population-rises-near-us-reactors.

[24]: According to U.S. Energy Information Administration 2003 data at http://www.eia.gov/electricity/annual/html/tablees1.cfm.

[25]: According to U.S. department of labor data at www.dol.gov.

[26]: According to U.S. department of labor data at www.dol.gov.

[27]: According to U.S. Energy Information Administration 2003 data at http://www.eia.gov/electricity/annual/html/tablees1.cfm.

Reference

Beckjord, Eric et al. 2003. *The Future of Nuclear Power*. Web. 9 Dec 2012. <http://web.mit.edu/nuclearpower/>.

Bickel, Peter and Rainer Friedrich, ed. 2005. *Externalities of Energy Methodology 2005 update*.

Cohen, Bernard L.. 1983. "Breeder reactors: A renewable energy source", in *American Journal of Physics*.1983.51 (1), 75–6.

Eeckhoudt, L., C. Schieber, and T. Schneider. 2000. "Risk Aversion and The External Cost of a Nuclear Accident". *Journal of Environmental Management*. 2000. 58, 109–17.

Gollier, C. 2002. “Time Horizon and the Discount Rate”, in *IDEI*. University of Toulouse, mimeo.

Pearce, D.W. 1979. "Social Cost-benefit Analysis and Nuclear Futures:, in *Energy Economics*. April 1979.

Pearce, D. W. 2003. “The Social Cost of Carbon and Its Policy Implications”, in *Oxford Review of Economic Policy*. 2003. Vol. 19, No.3.

Proult, D. and Desaigues, B.1993. *L’´ Evaluation de l’Impact ´Economique des Situations Post-accidentelles: Pr´esentation et Analyse du Mod`ele COSYMA*. CEPN Report. 1993. R-216.

Schneider, Mycle et al. 2011. "Nuclear Power in a Post-Fukushimia World", in *World Nuclear*

Industry Status Report 2011. 9 Dec 2012. <www.worldwatch.org/nuclear-power-after-fukushima>.

Till, C. E. and Y. I. Chang. 2011. *Plentiful Energy:The Story of the Integral Fast Reactor*. Create Space Independent Publishing Platform.

Tolley, George et al. 2004. "The Economic Future of Nuclear Plant". 9 Dec 2012. <www.ne.doe.gov/np2010/.../NuclIndustryStudy-Summary.pdf>.

Weitzman, M.. 1999. “Why the Far Distant Future Should be Discounted as Its Lowest Possible Rate”, in *Journal of Environmental Economics and Management.* 1999.Vol. 36, 201-8.