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# AN INTRODUCTORY SURVEY OF ECONOMICS AND NUCLEAR ENERGY[*]

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Abstract: The president of the United States has finally presented the long awaited energy policy of his government. Nuclear energy was specifically mentioned as a main weapon to combat the buildup of excessive greenhouse gases – whose existence was thus explicitly acknowledged – as well as to provide the energy that will be needed in the possible transition to what might eventually turn out to be a less energy intensive economy. As pointed out in my energy economics textbook (2000), in such a transition more energy might initially be required than ever for such things as the production of e.g. hydrogen: although thermodynamically a loser, hydrogen might deserve the status of an economic winner in a world where oil is scarce and motor fuel is valuable. Something else that might be needed is a better understanding of the simple economics pertaining to nuclear energy and its optimal use in electricity generation, since recent textbooks and other publications seem reluctant to take up this topic. I conclude this paper with a discouraging hypothesis about the 'plutonium economy'.

Key words: Fissile elements, Kyoto Protocol, merit order, option value

The purpose of this paper is to simplify some of the discussion of nuclear energy presented in my textbook on energy economics (2000a). I also attempt to update and correct an earlier survey paper (2000b) on the same subject. The incentive for this project was provided by the announcement of President George W. Bush that nuclear energy will be a cornerstone of his government's long awaited energy policy. Interestingly enough, on the same day as this announcement was made, a gentleman from a country that is overwhelmingly unfriendly to nuclear energy informed me that an opinion is gaining ground among his colleagues that the only way to achieve the Kyoto stipulations on greenhouse gases is via the decreased consumption of energy intensive activities by all categories of consumers, and/or a greater reliance on nuclear energy. Since the first of these can be completely excluded in the real as opposed to a soap-opera world, an increased resort to nuclear energy seems unavoidable.

Regardless of any decisions taken in Washington – or anywhere else – nuclear based electricity with its almost negligible output of greenhouse gases is due to enjoy a renewed popularity, sooner or later. It is impossible to verify the absolute *certainty* of excess 'anthropocentric' (or man-made) global warming – even if this assumption is supported by an overwhelming majority of top-level scientific opinion – however a mention of additional evidence to that effect appears constantly in both the popular and the scientific press. Just as important, the widely advertised 'fuel of the future', natural gas, is far less plentiful than widely believed. Well before the middle of the present century, the global output of gas will very likely peak, which means that even before then it should be clear that its price has departed permanently from the bargain-basement levels it achieved at various times during the last decade of the 20th century.

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[*] I would like to thank colleagues at the Department of Economics, Uppsala University, for their help with this paper.

An important reason given by the Bush government for rejecting the Kyoto Protocol had to do with it placing the United States at an economic disadvantage. But nothing would be more disadvantageous to *any* country than to reject inexpensive energy (e.g. nuclear) for economically unsure alternatives (such as gas and renewables). Arguments have been confected in virtually every part of the world that nuclear energy (from *best practice* installations) is more expensive than that obtained from e.g. fossil fuels or renewables, but this is mostly a gross misunderstanding with some prominent neurotic overtones. Economics is not an experimental science, but it so happens that important experiments take place all the time, and there is one involving nuclear energy and its comparative cost that deserves particular attention.

I am speaking here of the introduction of nuclear energy into the Swedish energy picture. On average, over the past decade, Sweden has produced electricity whose cost is the lowest or second lowest in the world. The other contender for the championship is Norway, where more than 95% of electric power originates with water – which is universally regarded as the least expensive means to produce electricity. For those persons who have decided to think otherwise, let me refer them to the cost and market price of Norwegian electricity over the past few decades where, until deregulation raised its illogical head, electricity consumers were especially favored.

About 43 percent of Swedish power is produced in nuclear establishments, while water is the source of most of the rest. Just by knowing this, and the near equality of electricity cost in the two countries, it can be shown by a few minutes of secondary school algebra that best practice nuclear installations of the Swedish variety rank with hydro as the least-cost producers of electricity. And there is more: if the recycling of nuclear fuel were permitted, then the average cost of electricity (in dollars per kilowatt-hours) would unambiguously fall beneath that of water based electricity. Of course, this might already be the case, since the extension of the ‘life’ of many nuclear reactors from 40 to 60 years will in some cases mean a drastic decrease in the capital cost. (A thorough non-technical review of this issue can be found in Hellman and Hellman (1983) as well as my energy economics textbook, but it is obvious that we can perceive the logic of this result by simply examining the basic ‘annuity’ formula, or $P_c = rP(1+r)^T/[(1+r)^T - 1]$, where $P_c$ is the total ‘periodic’ capital cost ( = interest + amortization), r the discount factor, P the price of the asset, and T the ‘length of life of the asset’. Ceteris paribus, at T increases, $P_c$ falls. The decline in $P_c$ as T increases can be obtained immediately by differentiation, but intuitively, as T increases, the amortization cost falls.)

What about the disposal of nuclear waste? My approach to this matter is not very PC, since it has to do with my belief that the nuclear reactor might deserve the title of the preeminent scientific invention of the 20th Century. Disposing of nuclear waste should turn out to be a far less complicated scientific problem, although it definitely is not the kind of thing that deserves to be treated lightly. *Ceteris paribus*, the assumption that I feel most comfortable with is that the same kind of persons who designed the first reactors are ultimately capable of solving the disposal problem – if they are allowed to. Here I would like to add that one of the probable reasons for the resentment of nuclear energy is that a thorough grasp of its interior mechanics requires the kind of study and application that is offensive to a large part of the late-night television audience.

According to the International Atomic Energy Agency, on 1 May, 2005, there were 441 nuclear plants in operation, with 27 being constructed. Furthermore, expectations are that at least 20 additional plants will come on line in the next 15 years. (South Korea, for example, is thinking in terms of 20 new plants.) Just as important, many installations are now being upgraded. For instance, for political reasons one nuclear plant had to be closed in Sweden, however upgrading of the remaining 11 enabled more than the lost *energy* to be regained. As a result, energy output in almost all countries with nuclear assets will probably be increasing all the time, even without the addition of new reactors. Nuclear energy accounts for just over 6 percent of the total global energy, but where electricity is concerned it supplies slightly over 16 percent.

One of the new plants under construction will be located in Finland. According to the Finnish government, this plant will "enhance Finland's ability to meet its Kyoto greenhouse gas targets." Finland's environmentalists have declared the new installation "dangerous", but possibly they have confused it with those in neighboring Russia and/or the Baltic countries, where there is a large amount of equipment (of the Chernoble type) still operating that could not possibly obtain a licence to produce electric power in Western Europe or North America. In any event, little or no mention was made by the government of the need to have access to inexpensive, reliable electricity, since in Finland as elsewhere arguments on that level are not likely to be welcome or understood by many persons who will be crucially dependent on that commodity. On this point I can add that if the nuclear reactor that was closed in Sweden had been kept open, and the profits it earned were turned over to the schools in Malmö (where the facility was located), the educational decline now being experienced in that city could easily have been reversed. The same thing applies to the health sector in Malmö.

This might also be a good place to note that a key statistic where nuclear energy is concerned is the capacity factor (which can be defined as *The actual energy produced in a given period divided by the (rated) capacity of the installation multiplied by the number of hours in the period*. This can be turned into percent by multiplying by 100). In considering the US, the average capacity factor is now above 80 percent, as compared to 58 percent in l980, where these figures do not consider annual 'down time' (which usually is about 3 or 4 weeks) for maintenance and inspection, while in Finland this down time is taken into account. Unfortunately, in many countries no clarification is provided concerning the method used to calculate the capacity factor, although it should be obvious that the second method is being used when we observe a reference to capacity factors that are greater than 100.

Finally, in a short appendix I provide some information on *option value*. In my textbook, I used this concept to discuss an aspect of nuclear 'downsizing', but here I prefer to apply it to undertaking – or not undertaking – investments designed to reduce global warming. The story in both cases is uncomplicated, and intuitively is almost certainly recognizable to everyone reading this paper: a value is placed today on the ability to avoid foreclosing future choices (i.e. options). Deriving the simple algebraic result given in the appendix involves no more than paying close attention to the language used to describe this process, which is largely borrowed from the seminal discussion in Dasgupta (1982).

## SOME BASIC PHYSICS AND ECONOMICS OF NUCLEAR ENERGY

The input-output description of a nuclear reactor is simple. (Natural) uranium in one form or another is transformed by a nuclear reaction to a substance with an extremely high temperature, which in turn heats water, and the steam that is raised goes through a turbine to a generator whose rotation produces electricity. Right away a dilemma is suggested by the possibility of insufficient water flowing next to the fuel, causing the kind of heating that leads to a literal 'meltdown' that particularly impacts on the base of the reactor. This is the kind of thing that voters in most countries do not want to have any part of, but fortunately equipment is now available – such as the *pebble bed reactor* – that cannot experience this kind of misfortune. The thing that needs to be appreciated here is that while energy produced from fossil fuel is the result of an uncomplicated chemical process, energy derived from nuclear fuel originates in the force binding the constituent parts of the fuel's atoms together, and its release necessitates the alteration of the structure of the atom itself. This can be an extremely complex process, though highly rewarding in terms of the energy that can be obtained.

The most common reactor is the light water reactor (LWR), of which the pressurised water reactor (PWR) is one variant, and the boiling water reactor (BWR) is another. The actual reactor operation is only a single element in what is know as the nuclear fuel cycle, because the storage and management of wastes is such an important activity. The total cycle begins with uranium mining and milling, and concludes with the management of uranium waste.

Next it should be understood that uranium – or better *natural uranium*, which is the reactor input – has 3 naturally occuring isotopes: U-235, U-238 and minute amounts of U-234. In this context an isotope can be regarded as a component of natural uranium (which will be explained in the next paragraph). The word 'isotope' literally means 'same place', and these isotopes occupy the same place in the periodic table of the elements, although there is a difference in their mass because they have a different number of neutrons in their nucleus. Of those three only U-235 is naturally fissionable, and thus capable of providing the kind of reaction necessary for the generation of electricity.

Unlike the others, U-235 can be made to split if its nucleus is struck by a slowly moving neutron. The mass of these fragments and neutrons is now somewhat less than that of the original nucleus and, most important, the reduction in mass has been transformed into kinetic energy (i.e. motion), which in turn is converted into heat as the fission products collide with surrounding atoms and are brought to rest. Other U-235 atoms may absorb the neutrons released by a previous fission, and themselves undergo fission. The release of neutrons leading to further fissions constitutes a *chain reaction*.

Prior to the activity just described, we have the mining of uranium ore, following which it is mechanically crushed, and uranium in the form of (impure) uranium oxide ($U_3O_8$) is extracted. This is commonly known as *yellowcake*, and much of the trade literature involves the availability of this commodity and its price. The production of yellowcake is the key step enroute to to the *natural uranium* mentioned above. Further purification and processing will yield uranium hexaflouride ($UF_6$), which is a feedstock for the *enrichment process* that will be considered directly below. *It is at this point in the fuel cycle that we have natural uranium*! (Natural uranium is sometimes referred to as uranium metal (U), and according to basic chemistry, it comprises 84.8 percent of $U_3O_6$.) The reader should note the difference between uranium ore and natural uranium.

The problem is that natural uranium contains only 0.7 percent U-235 (or about 1 part in 140), and most reactors require fuel containing, on average, 3 percent U-235. (That is to say, between 2.7 and 3.3 percent U-235.) Thus *if* enriched uranium is desired, an upgrading of natural uranium must take place.

The *front end* of the nuclear cycle is basically concerned with upgrading (or enriching) natural uranium to the required quality (i.e. richness). The 'non-upgraded' portion of the U-235 involved in the process is called *depleted uranium*, or *tails*. Professor Anthony D. Owen (1985) provides a valuable example in which 5.5. kilograms of natural uranium (with 0.711% U-235) becomes 1 kilogram of enriched uranium plus 4.4 kilograms of depleted uranium (i.e. tails) containing 0.2 percent of U-235. The front end consists of the first four stages of the nuclear fuel cycle, and stretches from the mine to the reactor core. The last two stages, whose purpose is to resolve the spent fuel problem, are called the *back end.* Here it can be noted the uranium typically accounts for 20-30 percent of nuclear fuel costs, which in turn account for 10-15 percent of total generating costs. The remaining fuel costs are due to various nuclear fuel services, such as conversion, enrichment and fuel fabrication.

What takes place in the reactor is a mass-to-energy conversion in which the amount of energy that can eventually become available is huge. (The expression "mass-to-energy" deserves attention because it is here that we have an overtone of Albert Einstein's work.) In theory, the energy output of 1 kilogram of U-235 is equal to that contained in 2,000 metric-tons (or *tonnes*) of oil, which is 2 million times as much in terms of weight. As mentioned, only about 0.71 percent of natural uranium is U-235. All except a minute amount of the remainder is U-238, which is unsuitable for the direct production of energy, because it captures neutrons without undergoing fission. This would greatly reduce the total energy produced by a given amount of natural uranium (U) were it not for another phenomenon. After capturing a neutron, the nuclei of U-238 transmutes into an unstable element that is not found in nature: plutonium 239 ( = Pu-239). Plutonium can also undergo fission, and thus both U-235 and Pu-239 are fissile elements, while U-238 is called a fertile element. The process by which a fertile element is converted to a fissile element is called breeding, and the breeder reactor is specifically designed to use the enormous amount of energy that is inherent in U-238 should intentional breeding take place. (Another fertile element is thorium 232, which is at least as abundant in nature as uranium.)

Reprocessing is one of two approaches to spent fuel management, and it involves chemically separating the plutonium, uranium, and radioactive residues found in irradiated fuel. The alternative is storing spent fuel in untreated or partially untreated form. There is a genuine economic dilemma here due to the difference in the *expected* present value of the cost of the two options, particularly since these costs are dependent on forecasts of future fuel supply, and the efficiency of waste management. Accordingly, there is scope for some ugly mistakes due to the inability to forecast future costs and prices with a high degree of accuracy.

In natural uranium the ratio of fissile to fertile atoms is 1/140, which indicates that without upgrading there would be a difficulty in maintaining the fission process, although slowing down neutrons with the help of a non-absorbent medium called a moderator will increase the probability of a neutron being absorbed by a U-235 nucleus. The most suitable method for enhancing fission is probably to use enriched uranium – because as I interpret the evidence this option is economically justified by existing and predicted costs. The enriched product is converted into uranium dioxide ($UO_2$) pellets, which are further processed into a form (e.g. fuel rods) which can be inserted into a reactor core. Now, with fission induced heat available, this heat can be utilized to produce steam, which is eventually transformed to the motive power for a conventional electricity generator. The power output is controlled by varying the population of neutrons in the reactor core.

It might also be useful to know that heavy water reactors (HWR) of the Canadian *CANDU* (Canadian deuterium uranium) type differ from the equipment mentioned earlier, since its basic fuel is non-riched (natural) uranium instead of the enriched commodity. The same is true of the Magnox reactors developed in the UK, and there are other designs. LWRs are shut down several weeks annually for inspection and maintenance, and during this period about one-third of the fuel rods are replaced. CANDU reactor are refueled continuously without interrupting their operation.

At least nine-tenths of all uranium used at present is enriched, and the enrichment stage accounts for about 50% of the cost of the nuclear fuel cycle. (The implication here is that it might be more economical to use equipment where enrichment is unnecessary, however this is not necessarily true.) The costs of enrichment are measured in *separative work units* (SWUs), which are a function of the effort required to separate U-235 from U-238. The proportion of U-235 remaining in the depleted uranium (the tails) that results from enrichment is called the *tails assay*.

Professor Owen and others have laid particular stress on the importance of the enrichment stage. New enrichment technologies (e.g. centrifuge and laser) have greatly reduced the energy needed to perform enrichment. As a result these technologies display a tails assay of around 0.10% instead of the usual 0.30% (on average). Since about ten percent of the OECD's uranium requirements are met from the supply of enriched tails, the large-scale adoption of these more efficient technologies could reduce the need for uranium by a significant amount. Adopting new technologies is a cost question however, and these investments are unlikely to be made before the price of uranium begins to escalate.

The back end of the cycle begins with the used (or 'spent') fuel elements being removed from the reactor: a reactor needs refueling when not enough U-235 remains to sustain a chain reaction. After being cooled, they are shipped to a reprocessing facility, where the fuel elements are reduced in size, dissolved in nitric acid, and various fission products are separated out. These are processed in various ways until shipment to a permanent repository become feasible. The thing to be aware of here is that the fuel has used up only a small amount of the total energy it contains. There are still some 'unburned' U-235 in the residue, and from an energy point of view, the plutonium in spent fuel contains a large multiple of the amount released by the 'burning' of the original load.

A 1000 MW installation can annually produce 15,000 cubic meters (= 15,000 $m^3$) of low-level waste, 1500 of intermediate- level waste, and 20 $m^3$ of high level waste. The high-level waste is difficult to neutralize. The first step is often vitrification (i.e. enclosing the waste in glass, which is then enclosed in steel containers). Final disposal might consist of buying these containers in deep holes in geologically inactive areas, etc. Eventually it may be possible to solve the nuclear waste problem by developing a reactor that completely burns up most or all of its fuel.

Uranium ore is mined in either underground or open pit installations from ores having a concentration that averages about 0.25 percent, if the concentration is measured in terms of uranium. It is sometimes measured in terms of uranium oxide, but this could cause some confusion because uranium oxide can be considered a processed form of 'raw' uranium.

The above numbers imply that about 400 tonnes of ore must be removed in order to obtain 1 tonne of natural uranium. The general abundance of uranium averages about 4 parts per million ( = 4 ppm) in the earth's crust, and 3 parts per billion in seawater. There are many estimates in circulation as to the amount of uranium that can ultimately be extracted from both onshore deposits and seawater, but all the figures that I have seen concerning possible extraction amounts strike me as being mostly guesswork, and so they will not be discussed here. Yellowcake prices have been low since the first (commercial) nuclear power station began operating (in the UK in 1956), but given the enormous electricity demand that could emerge during this century should, for example, a fraction of the 2 billion or more persons without access to electricity express their dissatisfaction politically or otherwise, this situation cannot be taken for granted.

Perhaps the most important part of Professor Owen's book for the present topic has to do with his discussion of the pricing of uranium and its various components. Among other things he has clarified the key role of inventories in this pricing. That immediately suggests the validity of the stock-flow model shown in Figure 1.

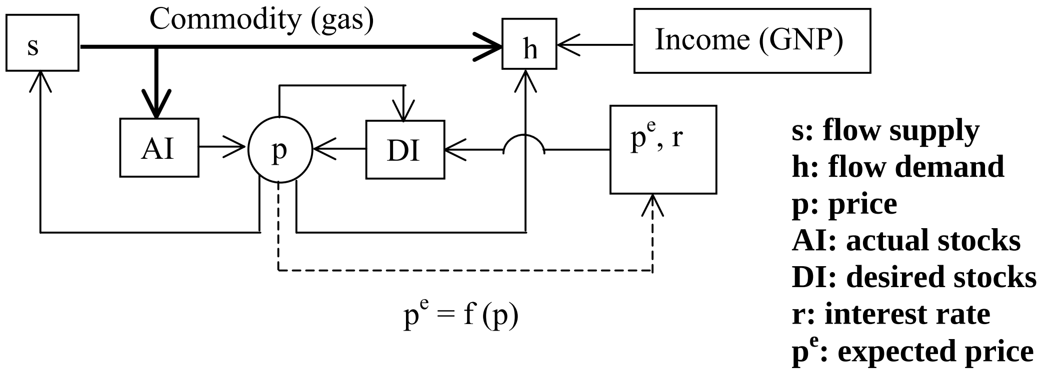


Figure 1

The current (or flow) supply goes into stocks (i.e. inventories) and current (i.e. flow demand. Price is formed by the relationship of actual stocks (AI) to desired stocks (DI), with the flow equilibrium [s(p) = h(p)] playing a secondary (but important) role. The equilibrium expression is therefore AI = DI, and when this situation prevails, s = h (because there is no addition or subtraction from inventories due to current supply and demand, and price is constant. Put another way, a stock equilibrium implies a flow equilibrium, while a flow equilibrium does not imply a stock equilibrium. In this type of model expectations are very important because of their influence on desired stocks, and in the real world expected prices are undoubtedly more difficult to describe than via the simple expression shown in the figure: pe = f(p). Let me also mention that in my textbook I extend this discussion somewhat, employing stock and flow supply and demand curves of a more general kind, as well as alluding to the kind of dynamic problems that are implicit in stock-flow models.

There is probably no point in exploring the mechanics of the fast breeder reactor (FBR) in the present contribution, except to say that it is principally concerned with converting as much as possible of the U-238 in natural uranium into fissile material, as rapidly and efficiently as possible, and then using it to generate electricity. It does the same thing for thorium. These reactors can also use depleted uranium produced in the enrichment process. This is why, in Japan and perhaps several other countries, the FBR is considered the ultimate solution to the electricity supply problem, although it is not the kind of thing to be sung at the top of one's voice in the local karaoke club. Some of the directors of the Japanese energy bureaucracy have made it abundantly clear that, as far as they are concerned, the conventional nuclear power station, which exploits just about one percent of the energy in its fuel, will ultimately be as extinct as the dinosaur, and must be replaced by the fast breeder, which extracts about eighty percent. They will also tell you, in private, that a Japan that can reduce its energy costs could have a substantial commercial advantage over those countries utilizing high-cost energy.

An intermediate step in this process may be a resort to mixed oxide (MOX) fuels. What we have here is the extraction of plutonium and uranium from spent fuel, and mixed with new fuel. The problem here is the possible contribution of MOX fuel to an 'explicit' plutonium economy, although since a recycling of plutonium can multiply the amount of electricity generated by the original load by a very large amount, the widespread concern for avoiding the highly disturbing presence of plutonium is unlikely to characterize the thinking of politicians for many more decades.

The price of yellowcake has moved in cycles for most of the past 4 decades, however I have never heard any serious complaints from firms on the buy side of the market. It may also be the case that the comparatively low price of that commodity has kept greater investment from taking place in more out-of-the way regions

A factor that has complicated the uranium supply-demand situation is the use of blended-down highly enriched uranium (HEU) from nuclear weapons as fuel for nuclear reactors. Present expectations are that at least 15% of OECD uranium requirements will be satisfied by Russian HEU, and perhaps some HEU originating in the US. As in the case of yellowcake, I cannot detect any scarcity of nuclear fuel nor the services for its provision. If there is a sign of a shortage, however, then it may happen that attitudes toward utilization of the breeder could change, and change rapidly, because in the not too distant future it will become clear to the television audience that the energy situation in the world does not provide grounds for optimism. Although it is not widely discussed, reprocessed Pu-239 can substitute for U-235 in that it can be mixed with U-238 (in the form of uranium oxide) to provide a fissile fuel known as MOX (for mixed oxides). This activity consumes more plutonium than it creates, and thus is not equivalent to 'breeding', but even so, the presence of plutonium on the input side of the process greatly offends environmentalists and the anti-nuclear movement. They claim that it is safer and more economical to store spent nuclear fuel than to reprocess it for reuse. The mixing referred to above takes place in a reprocessing plant of the type that the UK government has approved of for British Nuclear Fuels (BNF) Sellafield complex in north-west England. A great deal of attention has been paid to this installation, and the opinion here is that in the name of safety, the more attention the better.

## NUCLEAR IN THE LIGHT OF 'KYOTO'

Several years ago I published a paper in *Geopolitics of Energy* with the title 'Some aspects of Nuclear Energy and the Kyoto Protocol' (2000). On the first page of that issue, the editor of the journal, Vincent Lauerman, asked the following important question: "Is 'Kyoto' a lost cause without the mass deployment of nuclear power plants?
He added that "the curent debate on this topic is long on ideology and short on reason."

That almost sums it up. 'Almost' because basically what we are dealing with here is a shortage of the kind of information that would encourage not the "mass" but the *optimal* employment of nuclear facilities. (Optimal is a very important term in mainstream economics. It means choosing the *best* patterns of affordable consumption or production, given the presence of adequate information about available choices, and enough rationality to distinguish between different (e.g. good and bad) outcomes. In the *real* world, where intertemporal considerations dominate, this is asking for a great deal.) In any event, in theory, the general public's uncertainty where nuclear safety and waste disposal are concerned must be respected, while at the same time recognizing that a majority of this same public desires inexpensive and reliable electricity, as well as the absence of a dangerous accumulation of greenhouse gases. In particular, an excessive buildup of carbon dioxide ($CO_2$) is to be avoided. When all this is taken into consideration, we have an optimization problem that is analogous to those in e.g. your favorite intermediate level microeconomics textbook.

Ordinarily my approach to this quandary would begin with a reference to the greatest of all scientists, William Shakespeare: "*Time's glory is to calm contending kings, to unmask falsehoods, and to bring truth to light.*" The problem here is that we may not possess sufficient time to profit from this admirable *denouement*. My research has often focused on the bad things that could happen due to e.g. electricity deregulation and an unexpected shortage of oil, but these are trivial as compared to a global warming melodrama. Pacala and Socolow (2004) are absolutely correct in saying that in confronting the problem of global (or greenhouse) warming, "the choice is between action and delay", and as far as I am concerned, "action" means giving more weight to the nuclear option, beginning at once.

On the other hand, the possible consequences of delay can be inferred from the following brilliant observation by Gelbspan (1997):

> "Scientists do not know what hidden thresholds lie ahead. They do not know what feedbacks will take effect, or when. They do not know at what point an unstable climate will become a cascade down a steep slope. They cannot yet predict whether or when the rate of warming will accelerate. So those who are trying to avert the crisis are left groping in the dark, forced to choose arbitrary emissions-reduction targets that are determined more by their political viability than by their correspondence to the actual climate situation."

Returning to the first paragraph of this section, we are entitled to ask if an increased deployment of nuclear assets can 'save' 'Kyoto' – or more corectly, the United Nations Framework Convention on Climate Change that was broached at Kyoto, Japan, in December, 1997. The implicit conclusion presented below is that nothing can save 'Kyoto' except its (formal or informal) abandonment, and replacement by a more realistic alternative. As I pointed out elsewhere, "finding compromises that can satisfy all participants in the environmental wars must be as frustrating as the search for the Holy Grail (or the Fountain of Youth), but had the delegates at Kyoto genuinely believed that global warming (due to increasing atmospheric concentrations of greenhouse gases) constitutes a clear and imminent danger, they would also have realized that the final document served up to them by the behind-the-scenes grandees was grossly inadequate, and unless a radical extension of its provisions can be adopted (and implemented) in the very near future, greenhouse gases will continue their buildup in the same way that they have during the past few decades" (2000a).

(Something else those delegates would have done, if they had been serious persons capable of comprehending the subtler aspects of global warming, was to insist on the rapid adoption – if only in a token sense – of measures capable of reducing atmospheric pollution. As it happened though, most of them were too busy trying to ensure that they qualified for a ticket to the l998 climate warming get-together in Buenos Aires to become heavily involved with theoretical considerations.)

Will this buildup of greenhouse gas be instrumental in bringing about a collapse of our civilization and the destitution of coming generations? A large majority of our scientific elite say that it is definitely possible unless there are some drastic alterations in our outlook and behavior. Once again I would like to emphasize that to me this means doing something about the uncertainty mentioned earlier, which in turn calls for a greater reliance on nuclear energy. *With nuclear energy we know what we are getting. We are not investing in a $CO_2$ lottery!* Most of the rest – and particularly playing games with emissions permits, and/or the ivory tower gadgets and gimmicks favored by people like Amory Lovins – maintain or increase uncertainty via the fabrication and retailing of unproved and/or unprovable hypotheses and/or conclusions.

In the very long run, of course, we are moving toward what could be an exciting panorama of renewables and quasi-renewables. Whether this will turn out to be a comprehensive paradise on earth remains to be seen, although I for one have some problem believing that on a global scale, the corpus of economic and social losers will greatly diminish in size. The thing to remember here is that according to the OECD, two-thirds of the increase in energy demand between 2000 and 2020 will come from developing countries, where as already mentioned several billion persons lack an adequate or reliable supply of electricity. Some question should then be asked whether the persons experiencing this shortage prefer their future prosperity to depend on renewables or traditional sources of energy – where traditional in the present context means uranium or fossil fuels. If they choose the latter, then we might be talking about irreparable damage to the environment – and this could happen even if fossil fuels are quickly exhausted. (See Goodstein (2004) for an elementary examination of some aspects of this quandary.) But if that happens, then we are worse off than ever because of the steady increase in global population.

That brings us to the inescapable topics of natural gas and emissions trading. The best way to begin though is to compare the prospects for nuclear energy with those for oil. Arguably, the nuclear reactor was the most impressive scientific achievement of the twentieth century, and if governments become more cooperative, enormous improvements in this equipment are not only possible, but certain. It is also clear that science and technology have performed miracles where the search for and production of oil are concerned, and many observers expect that the oil wolf will never appear at the door because even more magnificent achievements are possible with the full utilization of things like supercomputers. However – *unlike* the situation with nuclear energy - some of us believe that these achievements are aimed toward finding and producing oil that – according to a large and growing consensus of geologists – will never be found because it does not exist. Eventually the same situation will prevail for gas.

There are many topics that are appropriate and accessible for a paper of this nature, however there are certain issues that need to be *brought* in the most direct manner to the attention of everyone with the slightest interest in the subject.

The first has to do with the increased use of natural gas to reduce greenhouse emissions: gas has often been portrayed as the perfect replacement for nuclear energy. Gas contains much less $CO_2$ than oil, and a great deal less than coal. Moreover, there is a very large amount of gas in the crust of the earth, and prospects are that a considerable amount will still be uncovered. Thus, in the light of what we have seen in the first six or seven years of the last decade – particularly in places like California and the UK – gas appeared to be just the thing needed to fuel the electric sector (instead of e.g. coal and nuclear). And it needs to be unconditionally recognized that that sector is going to need a great deal of fueling, because the demand for electric power is increasing at a much faster rate than often predicted. In addition, technology has provided some good news for consumers of gas: as a result of the development of combined cycle equipment that has greatly increased the efficiency of gas turbines, the cost of a unit of gas-based electricity was been palpably reduced (*ceteris paribus*).

Now for the bad news. Even persons who have studied economics at the advanced level often fail to note that when comparing the cost of electricity generated in nuclear installations to that of gas-based facilities, there is a widespread tendency to concentrate on *capital costs*, where (on a per-unit of electricity generated basis) the cost of gas (on average) appears to be one-half that of nuclear. However in a short article in *The Spectator* (2004), Rod Liddle says that according to the UK Royal Academy of Engineering, nuclear is the least expensive way to generate a unit of electricty: on average, it is one-half the cost of coal, and about 40% less than the cost of gas. *Some observers might be offended by this claim, however it is quite clear to me that when the present and likely future variable costs of generation are taken into consideration, and not just capital costs, nuclear is not at a disadvantage to any other technology! I can also refer here to a recent piece in the Financial Times by Andrew Taylor in which he discusses the cost of nuclear electricity with respect to gas based, but considers only the capital cost of nuclear. Once this mistake is corrected, we get an entirely different picture. The future price of natural gas relative to uranium – particularly as the global peak output of gas approaches – could reach a level where nuclear has an enormous cost advantage. A nuclear plant constructed today will have a 'life' of 60 years, or longer, and halfway through this period the price of gas could go into orbit.*

The same kind of reasoning has turned up in France, where a former prime minister, Lional Jospin, organized a study to clarify the competitiveness of gas with respect to nuclear energy. Jospin's instructions were to take *all* costs into consideration, to include those of an external nature (e.g. environmental costs). The conclusion, which was put into a 288 page report, was that there would not be great cost differences between gas and nuclear as long as there was no escalation in gas prices. As things turned out though, not long after the contents of the report had been fully digested by anxious readers, the price of gas almost doubled. Thus, another potential controversy involving 'greens' and their adversaries could be removed from the government's table, although those persons with a "no thanks" approach to nuclear power continued to be unimpressed or for that matter uninterested in arguments with a pronounced reliance on facts and figures.

As in the US and elsewhere, the 'life' of *existing* Swedish nuclear installation are now being extended to 60 years. By itself, this would mean that it pays to upgrade these facilities, but in addition there has also been a steady increase in *capacity factors* that makes upgrading even more attractive. On this point it should be mentioned that in the new deregulated Swedish electricity market, any decrease in nuclear capacity will increase the price of electricity in such a way that with the increased profits accruing to electricity wholesalers (i.e. generators), it will be possible for Swedish energy firms to increase their purchase of assets in e.g. Eastern Europe, many of which are heavy contributors to atmospheric pollution. As for Swedish consumers, they no longer count for much in this game, since it was their sheep-like passivity that allowed misfortunes like electricity deregulation and the dismantling of the nuclear sector to begin.

Life extensions are also almost certain for the bulk of the UK's nuclear capacity, especially since the prime minister, Tony Blair, has said that "if you are serious about climate change, then it's wrong to close the door on new nuclear development." A group in Sweden called "Environmentalists in favor of nuclear energy" would almost certainly agree with this evaluation. Another item that is relevant here is that natural gas not only contains $CO_2$ (though not nearly as much as oil), but methane, and some researchers say that if very large quantities are involved, methane can pose environmental dangers on the order of excessive $CO_2$ .

At the Kyoto meeting, nuclear energy was by and large overlooked, and probably was not even on the agenda, however it was decided that a market would be established for the trading of emission permits. For some reason this concept has captured the enthusiam of the high- and-mighty, and once this emissions bazaar is fleshed out with confused buyers and sellers of permits, and bright-eyed young people functioning as market makers and/or brokers, it will fit perfectly the role of a *pseudo-market*, to use the terminology of the New Zealand economist Owen McShane. In concept, though perhaps not in layout, it will likely be similar to the uniformly inefficient establishments introduced to enable the risk associated with electricity deregulation to be hedged.

I hope that I am not revealing my basic frame of mind in this matter when I say that emission permits are one of the worst ideas ever formulated, and the cost – both in dollars and millions of tons of $CO_2$ launched into the atmosphere – would make it a distinguished non-starter if there had not been a small group of academic economists, and a large group of finance professionals, who expected to gain personally from their introduction. These ladies and gentlemen were able to take advantage of the lack of genuine economics expertise that characterizes the environmental ministries of most governments, to include exterior experts at their disposal.

'Most governments' however does not include the US government, where the shortcomings of emissions trading – though not extensively discussed – are perfectly understood. A deputy US energy secretary once informed a Senate committee that an excessive dependence on gas was a threat to US energy security, and made it clear that more nuclear power belonged in the US electricity generating portfolio. What he undoubtedly meant was that a threat to energy security was a threat to the US macroeconomy. This kind of logic is very definitely understood – though not perfectly – in Sweden, and therefore Swedish industrialists do not hesitate to make it clear that among the costs of emissions trading and the higher energy prices that will almost certainly be entailed, an accelerated movement of Swedish industry toward what are sometimes called 'low wage' countries should be included. At the same time though, many of these 'captains of industry' have not made a substantial effort to convince their counterparts in government to become more enthusiastic about nuclear energy, because their primary loyalty is to salaries and bonuses, and these can be maintained even if their manufacturing facilities are in Poland or the Baltic countries or Pago-Pago.

I doubt whether all readers of this contribution will appreciate merely being told that emissions trading is a costly misadventure, and the best thing to do is to ignore it. Let me therefore suggest that they should ask their favorite economics teacher for a deeper insight into the interior logic of this undertaking, or for that matter consult the superb microeconomics textbooks that are now available. At the same time I feel obligated to assure them that all the pages in all the textbooks that have been written since Adam and Eve will not help those noble economists, civil servants and students who hope to secure the expertise required to give an explanation of emissions trading that is capable of getting intelligent persons to see its merits. As President Putin was summarily informed, "it's a scheme to make money, and has nothing to do with surpressing pollution." Let's put this another way: by adopting emissions trading instead of a direct and systematic program for reducing greenhouse emissions (via e.g. nuclear energy, and emission taxes and subsidies), a lottery has been chosen instead of what might be a sure thing. There are, of course, good reasons for choosing lotteries instead of sure or near-sure things, but not when it involves the future of the planet.

At the 1998 European Nuclear Conference, Dr Hans Blix – who later became heavily occupied in the search for 'weapons of mass destruction' – provided delegates with a series of highly relevant queries. These were reviewed in some detail by Smosarski (1998), and one of the most interesting was that in France, which generates close to 80 percent of its electricity in nuclear installations, the emissions of $CO_2$ per kilowatt hour were about 64 grams, while in the UK, which had a much smaller amount of nuclear, and as a result uses a considerable gas and coal, emissions were 10 times larger. Similarly, in Sweden, where nuclear and hydro generated most of the electricity, the figure was 58 grams/kilowatt-hour, as compared to Denmark – which even at that time had a large inventory of wind turbines, but relied for the most part on coal – the figure was 917 grams/kilowatt-hour.

What is not generally understood is that the Danish resort to windpower can be justified by the high cost and pollution that characterizes their dependence on coal. This situation does not apply to neighboring countries, and in particular Sweden and Norway. It is also interesting to note that the use of windpower appears to be peaking at the present time, which may be due to the inability to fit it into the deregulated Danish electricity market – which, like most deregulated electricity markets on the face of the earth has encountered considerable difficulty in honoring its promises to the households and firms of that country. This might also be the place to inform coal intensive Denmark that a 1000 $MW_e$ coal-fired power plant releases almost 100 times as much radioactivity into the environment as a comparable nuclear plant. In addition, as the World Nuclear Association pointed out, "if all the world's nuclear power were replaced by coal fired power, electricity's carbon dioxide emissions would rise by a third".

While on this subject it can be noted that according to Liddell, 18 million tonnes per year of $CO_2$ is avoided because of the presence of the UK's nuclear energy, which he states is equivalent to five car-free days per month. For Europe as a whole, Dr Blix says that nuclear power helps to avoid the emission of approximately 700 million tonnes of carbon dioxide a year. This is a very large number, and one would like to think that had it been circulated to the several thousand delegates at Kyoto, or the 60,000 at Capetown for the so-called 'World Summit', enough of them would have been sufficiently motivated to put their eating and drinking aside long enough to realize that there was a short cut to environmental sanity that did not involve the uncertainties implicit in the 'green message'.

The problem here is one of rationality on the part of the taxpayers who sponsor and support mastadon holiday outings like those at Kyoto, Capetown and elswhere. My favorite example has to do with the willingness of a large number of the Swedish people to accept a program for nuclear retreat that is completely inconsistent with their overall 'revealed preferences'. A great majority of Swedes want full employment, adequate pensions, lower taxes, high-quality health care and education, a great deal of leisure, public order, and an efficient defence. They have also shown themselves to be willing to accept a high level of expensive immigration, while at the same time aspiring to spend 1% of the Swedish gross national product on what they think of as aid to developing countries (but which to a considerable extent is spent on weapons and plane tickets).

All of these goals – laudable and otherwise – are in the danger zone if the wrong kind of decision is taken about Sweden's energy supply. As bad luck would have it, sub-optimal decisions on this front are not just possible but likely, because the uncertainties associated with the present Swedish economy have greatly inhibited clear thinking on the part of the electorate. For instance, it is widely recognized in Sweden that raising the energy efficiency of homes and other structures, and vehicles, can yield sizable economic gains, but enormous expenditures associated with the Swedish entrance into the European Union have greatly reduced the scope for almost all socially profitable energy investments (to include health and education). There is also a remarkable lack of clarity in thinking about the proposed use of natural gas, where the issue is not just pollution, but the inevitable escalation of its price.

## SOME NUCLEAR ELECTRICITY FUNDAMENTALS

Electricity dereguation has failed or will fail everywhere, mostly due to the lack of investment in new capacity. Put another way, the only place where it apparently functions as predicted is where there is excess generating capacity. Governments that must answer to voters want more capacity, and perhaps they will get it, however they should be aware that deregulation and nuclear energy would have difficulty coexisting.

The reason can be determined by a close reading of intermediate microeconomics texts. One of the great dreams of the deregulationists is to convince the general public that *increasing returns (or decreasing costs) to scale* do not exist, and that the future lies in small scale installations. This pernicious delusion has been sold to many voters and decision makers, but this does not make it a reality. It will be even less so in the future when the rise in gas prices will tend to restore what historically appears to be, *on average*, the conventional 'merit order' in electricity generation, which tells us *where* and *how much* of the currently and eventually available equipment will be used.

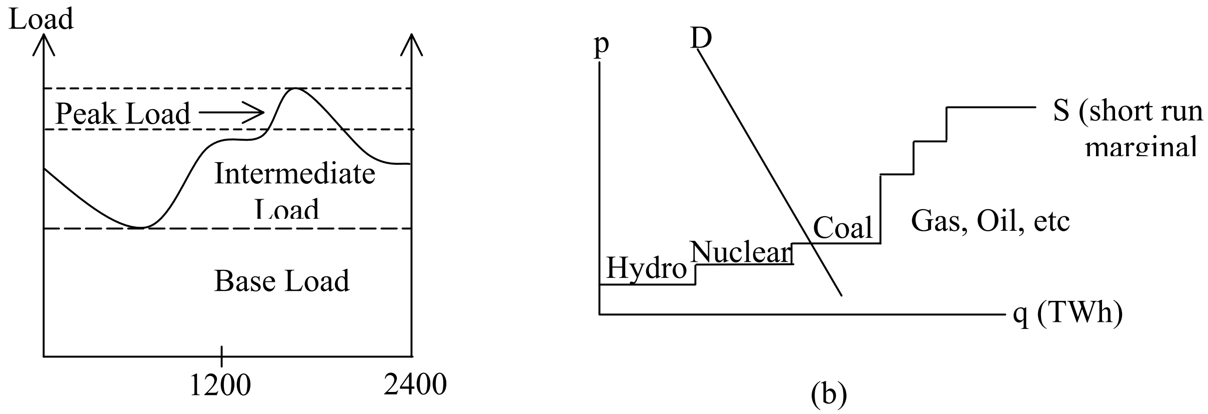
In nuclear intensive countries – such as Sweden, France, Belgium, etc – what we will ideally have is very large nuclear plants 'carrying' the *base load* – which is the load that is on the line all the time – while at the other end of the spectrum new gas equipment will largely be earmarked for carrying the *peak* load. (At the time I wrote my textbook, a weighted global average indicated that 60% of the power output was base load, while only 10% was peak load.) In very large countries such as Canada, the United States, and perhaps Brazil, a similar pattern would apply to regions (rather than to the entire country). Hydropower carries both the base and the peak load in Norway, since in that country more than 95% of the electricity is water based power, while in Denmark coal is the main source of the base load. Hopefully, this section will help to clarify the terminology and logic of this topic, which was spelled out at considerably greater length in my textbook, and is much more important than commonly realized.

In between the base and peak load, we have the intermediate load. Coal is often found here, although in theory this might be true of any fossil fuel. It also appears to be the case that coal is often responsible for the base load in regions where there is no nuclear, and the peak load where there is no gas. The point is to be flexible in these matters, however it is not easy to conceive a situation in which nuclear would supply peak load energy. The reason for this is that given the large capital costs of nuclear, it would be uneconomical to have this equipment standing idle for long periods of time.

In Sweden the base load is carried by both nuclear and water, while the peak load is carried by water, but there a dream in Sweden to turn the base load over to gas, since in the very recent past, the fall in the price of gas made it a good candidate for the base as well as the peak load. As the price of gas is now developing, the merit order in most countries appears to be reverting to the usual historical pattern. This will take time, because increasing gas prices do not mean that gas-fueled equipment (adopted when gas prices were low) that presently supply the base load will be summarily junked. (In the perfect world of neo-classical economics, this equipment would never have appeared.)

Some of the previous discussion probably caused readers difficulty, because there has been a widespead tendency among non-electrical engineers to ignore the optimal plant mix (i.e. merit order). This is unfortunate, because what we always see in the real world is a mix of electricty generating techniques, even though the application of conventioal demand curves to so-called electricity supply curves might suggest that – in the long run at least – only one generating technique is required. For example, in countries like Japan and France, it might be possible to argue on the basis of mainstream supply-demand analysis that all electricity should be generated by nuclear facilities, since the marginal cost of this electricity is appreciably lower than that obtained from e.g. coal and gas. As observed above, in general this argument is wrong.

What we need to understand here is the crucial importance of the structure of demand: the demand for electricity typically varies during a day in the cyclic manner shown on the left hand side of the following diagram. This is a much different proposition from the highly stable demand curves that we deal with in our courses in microeconomics, and also vastly different from the scheme that we see on the right hand side of the diagram, which occasionally appears in important official documents as well as classrooms, where it is used to draw conclusions that are presented to politicians, their advisers and students as scientifically credible, though actually they are false.



(a)

(b)

# Figure

Along with the demand contour, it is necessary to understand the different cost characteristics of various types of generating equipment. For instance, even though the marginal running cost of nuclear equipment is very low, while that of gas is very high, the algebra required to show that it is much more economical to use gas rather than nuclear for generating peak load electricity is extremely simple. (The reason of course being that the capital cost of nuclear equipment is too high for it to stand idle during the non-baseload periods.) This might also be the right place to say more about Figure 1-b, which shows a conventional demand curve, and a more-or-less conventional supply curve. The usual interpretation of the arrangement in this diagram is that no electricity should be generated with oil or gas, but as already suggested, such an interpretation is highly misleading. More important, at best this kind of diagram has only a minimal utility where the present subject is concerned, although the day before writing these lines I suffered through an entire seminar where this was not understood.

Without naming names, there is considerable opionion in certain quarters that low cost and high efficiency will be essential characteristics of future power plants, and non-nuclear technologies are developing rapidly in this direction. Everything is relative in this old world of ours, and as a result I find that opinion completely incorrect at the present time. It also appears that when attempting to calculate the cost of various energy sources, there is a tendency to use a fairly large discount rate (e.g. 10%), and not to take into consideration such things as ‘best practice facilities’ and the length of life of nuclear plants. If all nuclear facilities were of the same quality as those in Sweden, the global nuclear cost picture would be entirely different. It may be true moreover that extending the life of nuclear plants to 60 years compensates for excessively high discount rates. Interestingly enough, here in Sweden, nuclear opponents are doing everything possible to claim that nuclear plants with half this ‘age’ are unsafe, when in truth they were probably the most safe in the world until deregulation put in an appearance.

## A CONCLUSION

Philip H. Abelson was the energy editor of *Science*, one of the top scientific publications in the world. Several years ago he published a short article called 'Decreasing reliability of energy' (2000). The word 'nuclear' did not appear in Abelson's exposition until the last paragraph, and then in conjunction with a warning that because of the changes that often take place in global energy realities, energy policies will need continuous monitoring and periodic revision. However, on the basis of the considerable shortcomings displayed by gas and coal that he mentioned previously, it might be suspected that a larger nuclear commitment might avoid some of this bother. Unfortunately, there is still this business of nuclear waste in the picture, but for anyone with a genuine faith in mainstream science, it is quite obvious that in the long run dealing with this matter is less of a problem than designing the equipment that caused it.

A caveat might be in order here. Discomforts due to decreased reliability and higher prices are of less interest to me than the global warming puzzle. I can live with higher electricity prices, but news of rising water on the Reeperbahn (in Hamburg) or Canal Street (in Amsterdam) might be more difficult to shrug off. Brilliant observers like Sonja Boehmer-Christensen (the editor of *Energy and Economics*) and Leonard Brookes (now a consultant and analyst, and formerly responsible for economic forecasting and energy policy at the London headquarters of the UKAEA) have assured me that the global warming issue contains some facets that cast a shadow on my 'faith based' approch to the subject, however I must confess that I am powerless to resist the kind of argument that might have been presented by a man often called 'the best brain of the 20th century', the late John von Neumann. In his seminal articles and the famous book that he wrote with Oscar Morganstern (1944), he concluded that *SAFETY FIRST* was almost always the best strategy for high risk activities – i.e. activities where there is a significant probability of 'ruin'. I hope that I do not have to say that this is essentially what the former Prime Minister of the UK, Margaret Thatcher, meant when she once suggested that where global warming is concerned, it might be a good idea for political decision makers to avoid making wagers that their foot-soldiers cannot afford to lose.

One more observation seems useful here. Almost 25 years ago I attended a conference in Canberra Australia in which one speaker said that the sooner the breeder reactor was put into use the better. I did not talk to anybody who agreed with him – in fact, many listeners obviously thought that he had to be suffering from a serious mental disability in order to entertain those thoughts – and I believe that such would be the case at the present time, but even so I now suspect that the plutonium community is inevitable. The huge amount of energy in plutonium will eventually overcome arguments that that it is an undesirable component of the future energy economy.

Of course, it is impossible to say exactly when this will happen, but I suspect that a sustained movement will begin in that direction fairly soon after the global output of oil and/or gas peaks, or even if a strong belief emerges that there is not enough uranium to supply conventional reactor fuel: either one of those events will be the Pearl Harbor or 9/11 of the energy decision makers in the US, and after that the rest of the world will have no choice but to join the parade. Everything considered, this is not something to look forward to, however one hopes that wise voters and decision makers will do everything possible to ensure that *if* it is destined, the plutonium economy arrives very late, and leaves very early, and during its visit it does as little damage as possible.

## APPENDIX: OPTION VALUE

The introduction to this paper contained a few comments on *option value*. Much of the option value literature is pedagogically confusing, however the logic is quite elementary, and involves no more than realizing that if the environmental effects of today's investment and/or consumption activities are irreversible and uncertain, then we should think about ensuring that future options (i.e. alternatives/choices/preferences) are not foreclosed or unduly restricted by present actions – assuming of course that we are concerned about the future. The way this problem is usually tackled is to calculate a sum of money that we would require in order to undertake a risky and irreversible project.

Put more formally, option value is sometimes described as the amount a risk-averse person would be willing to pay to prevent an irreversible investment taking place which involves a risk that cannot be avoided through conventional insurance. Of course, in the light of the above, this could be put another way: it is the amount that a risk-averse person would have to be paid (above a normal profit) to make this investment.

Option value is often – though not always – distinguished from *quasi-option value*, which is the amount that a person would pay for information (about future states of nature) when the outcome of a given investment or consumption activity is irreversible. (See e.g. PJ. Crabbe (1984).) The finer points of these two definitions will not be mulled over in this short discussion, however I consider it appropriate to note my faith in the great majority of scientists who proclaim that the atmospheric environment should be kept as close to its present state as possible until adequate information is available about the costs *and* benefits of making large changes that for all practical purposes are irreversible.

The following algebra will derive a result that I first saw presented in a seminar at the Stockholm School of Economics, and which I immediately condemned as trivial. On second thought however, I have come to the conclusion that it is not quite trivial, and this is especially true of the logic I use below in obtaining it, which I have attempted to make more systematic than in the literature that I have encountered. The first step is to introduce a simple diagram whose components will be clarified in the ensuing discussion.

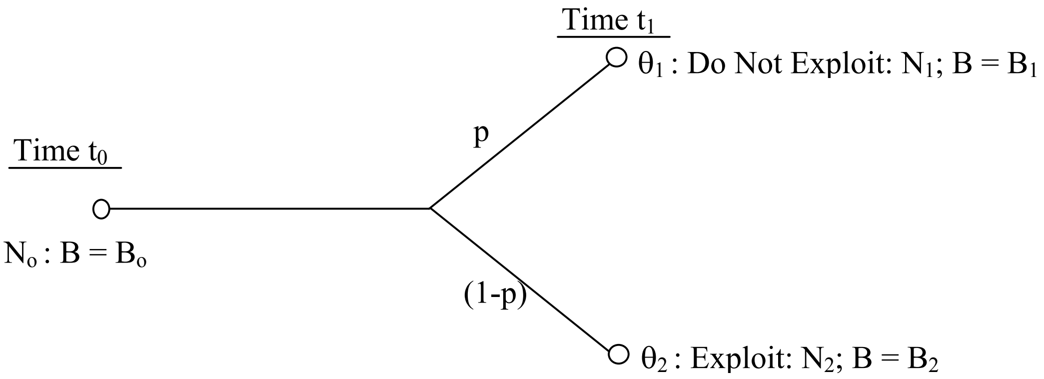


Figure A1

1) The possible states of the world are $\theta_1$ and $\theta_2$, with probabilities p and (1 – p). $\theta_1$ involves a situation in which the exploitation of an atmospheric asset results an unfavorable outcome, while the state $\theta_2$ is favorable socially and/or economically. For example, an investment that (*ex-post*) turns out to not cause any appreciable harm to the atmosphere.
2) The social benefit (measured in money) from being in the two states are $B_1$ and $B_2$, as shown in the diagram. In addition $B_1 < 0$ (i.e. a loss), and $B_2 > 0$. The sign of $B_0$ can be considered later.
3) $N_0$ is the *marginal* amount of the atmospheric asset exploited at time $t = t_0$. It is taken as unity, and so we have $0 \leq N_0 \leq 1$, but e.g. the '1' could signify one million units of 'something'.
4) We can now write an expression for the present value ( = PV) of the *expected* social benefit realized because of the exploitation of an amount $N_0$ of the atmospheric asset. Here it can be noted that the atmospheric asset might be 'unpolluted' – or realatively unpolluted – air, or something similar, that can be 'exploited' at $t_0$ by e.g. investing in a new power plant that burns a fossil fuel. A *social* rate of discount 'r' is applied to the *expected* benefit in period $t_1$ (which is the numerator in the second term on the right hand side of the following equation). In some cases this can be taken to be the interest rate.

$$\mathbf{PV = B_0N_0} + \frac{pB_1N_1 + (1-p)B_2N_2}{(1+r)}$$

5) *If* we find ourselves in the bad state then we choose $N_1$, while if we find outselves in the good state then we would choose $N_2$. Something else that should be appreciated here is that whoever is making the decisions is risk neutral, otherwise the B's would have to be expressed in 'utility' rather than monetary units. We can also specify that $0 \leq N_1, N_2 \leq 1$, and soon we will discover what we should have for the sign of $B_0$.
6) At this point the language becomes important. Given $N_0$, if $\Theta = \Theta_1$ (the bad state) results, then $N_1$ should be $N_0$: there should be no further exploitation of the asset, and irreversibility keeps us from making $N_1 = 0$. But if $\Theta = \Theta_2$ then we would choose $N_2 = 1 - N_0 = 0$, which is obtained by full exploitation of the (marginal) atmospheric asset in period $t_0$, or $N_0 = 1$. *Observe what is happening: we are thinking about how we should act now(i.e. at the present time) in dealing with the possible outcomes of a risky, irreversible situation.* This allows us to write the expression for PV as:

$$\mathbf{PV = [B_0} + \frac{pB_1}{(1+r)}\mathbf{]\,N_0}$$

7) We see immediately from this expression that in order to have PV > 0 we must have [$B_0$ + ($pB_1/(1+r)$] > 0, or $B_0 > -$ [$pB_1/(1+r)$]. *$B_0$ is the option value and it is positive, since $B_1$ is negative*! In looking at this expression we should be able to see why I called it trivial at first sight, but something that is often missed (along with getting the sign of $B_0$ wrong) is that the larger p and/or the smaller r, the larger is the option value. For example, if we were thinking in terms of private enterprise, $B_0$ is the amount that the potential exploiter/investor would have to receive in order to undertake this particular risky project, in addition to the normal profit.

If we were thinking in a 'social' sense, it is the amount that he would have to pay to the persons liable to be damaged by his investment, and who would be in a particularly bad situation because of the irreversibility of the arrangement. This makes sense because, for example, if r (the social discount rate) were put equal to zero, it means that whoever is making the decisions considers that *at the present time* the welfare of future generations should be valued as highly as the present (decision making) generation. This might have been viewed skeptically a decade or so ago because at that time almost everyone believed that, on the average, future generations would live in luxury as compared to the present.

There is some ambiguity associated with the above analysis, however this is in the nature of academic economics, where for the most part practitioners deal with 'models' rather than reality. The original presentation of option value many years ago had to do with transactors who were obliged to sell options, although had it been possible – which ostensibly it wasn't – they would have hedged against uncertainty by purchasing insurance. Needless to say, 'efficient' markets for option transactions that are based on the possibility of *immense* climate changes are unlikely, nor is it conceivable that they will ever be available – despite the claims about 'catastrophe derivatives' in various financial publications. On the other hand, institutions are supposedly coming into existence that will make possible the large scale trading of emissions permits, but since *maintaining* the atmospheric environment is an important *public good*, it could be argued that a carbon tax is more appropriate than a lottery – given the experiment with electricity deregulation. Put somewhat differently, we might be better off if, instead of working overtime to demonstrate their cleverness, economists and heavy-duty thinkers who are in a position to influence the high and mighty of this world would focus on prudence and clarity .

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Geoffrey Rothwell, Principal Economist, Nuclear Development Division, OECD/Nuclear Energy Agency (NEA); formerly of Stanford University. "â€¦ [an] excellent, accessible, and thorough primer on the policy issues surrounding nuclear power â€¦ a text highly recommended for courses in energy policy and safety regulation, and for readers interested in nuclear power as an alternative to fossil fuels." T. Brennan, Choice. Book Description.Â  He has advised many international bodies on energy policy and the economics of regulation, including the International Energy Agency, the OECD and the European Commission. He is the editor of energypolicyblog.com. Read more. New nuclear power plants typically have high capital expenditure for building the plant. Fuel, operational, and maintenance costs are relatively small components of the total cost. The long service life and high capacity factor of nuclear power plants allow sufficient funds for ultimate plant decommissioning and waste storage and management to be accumulated, with little impact on the price per unit of electricity generated. Other groups disagree with these statements. Additionally, measures to Rev. ed. of Introductory nuclear physics/David Halliday. 2nd. ed. 1955. 1. Nuclear physics.Â  It can be used specifically for physics majors as part of a survey of modern physics, but could (with an appropriate selection of material) serve as an introductory course for other areas of nuclear science and technology, including nuclear chemistry, nuclear engineering, radiation biology, and nuclear medicine. 1 The Economics of nuclear power. World Nuclear Association. URL: http://www. world-nuclear. org/uploadedfiles/org/info/pdf/economicsnp.pdf (accessed: 15.01.2018).Â  Nuclear energy is one of the highest scientific achievements of the mankind, so for obvious reasons it cannot be fully implemented by a single company. Nuclear power production is inextricably intertwined in all major processes in the life of a country and the society. It is integrated into them, and the degree of this integration determines its security, the quality of life of the population, and in some countries (like Japan) the state of the entire economy.