Economics and Nuclear Energy: a Modern Survey

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Abstract

This survey is an extension of the first lecture in my recent course at the Asian Institute of Technology (AIT), paying particular attention to Sweden. Why Sweden? Because mainstream academic economics is interested in optimal arrangements, and this describes the Swedish nuclear sector, where the cost of nuclear-based power may still be the lowest in the world. Just as significant, for over a decade politically motivated efforts to eliminate nuclear as an energy mainstay have not been successful. Many observations below have appeared in my previous work, particularly my energy economics textbooks (2007, 2000), however the incentive for the present paper was provided by the recent book of Bertrand Barre and Pierre-Rene Bauquis (2008), as well as valuable discussions on nuclear matters in the forum EnergyPulse (www.energypulse.net).

A dominant theme below is that a new energy economy must eventually be brought into existence, which could mean an expanded nuclear component. Some mathematics appears in the third section of this exposition, but much of it can be ignored if it makes the reader uncomfortable.

Key words: *Power Generation, Nuclear Fuel Cycle, Nuclear Costs.*

Introduction

As is well known, nuclear energy is not a popular medium with everybody. Even in France, virtually the capital of ‘the peaceful atom’, there are many persons who hope that someday another energy source will replace all or a large part of the 80 percent of the electricity supply that originates with nuclear. Frankly, even if there were a major accident in France, or a nearby country, that yearning seems unrealistic. In countries like France and Japan, where energy independence is paramount, nuclear energy is not there to be questioned but to be exploited. ‘No oil, no gas, no coal, no choice’ is the way the French put it, and although the energy prospects of many other countries may appear to be rosier, they could find themselves mouthing the same melancholy tune some day.

This does not mean however that it makes economic sense to consign conservation, renewables and/or other non-conventional energy sources and strategies to the margins of the energy scene. The ugly fact of the matter is that the world would probably be in a very bad

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way if these things do not become prevalent in a few decades, or perhaps even sooner, because they might have to accommodate a very large part of the energy load in all except a few lucky countries. But one way to make sure that they will *not* be available is for a majority of the voters in a given country, or even a decisive sub-set of the voters, or for that matter just the decision-makers to circulate the twisted hypothesis that it is already economical to introduce these items on a large scale.

The expression “an enigma within an enigma” was occasionally used by Winston Churchill when attempting to evaluate the former Soviet Union. I have employed similar terminology when discussing the attitude of Swedish politicians toward nuclear-based electricity (since, on the whole, their position differs markedly from that of their constituents). Statistics and a simple algebraic demonstration of the type given later in this paper made it clear that in terms of reliability and cost, the Swedish nuclear sector might be the most efficient in the world, and it is due to these characteristics that the irrational nuclear retreat in this country has been at least temporarily halted. The key departure here was upgrading the ten remaining reactors so that they could produce the same electric *energy* (in kilowatt-hours/year) as the original twelve reactors. As a fraction, this is roughly 47 percent of the total generated energy. (Approximately the same amount is accounted for by hydro.)

Lenin once remarked that socialism should be defined as communism plus electricity. The implicit assumption in Sweden after the Social Democrats assumed power was that something called the ‘Swedish welfare state’ would feature social democracy plus electricity. The way this was pictured as working is straightforward, and turned on mainstream economic logic: a high electric intensity for firms, combined with a high rate of industrial investment and the technological skill created by a modern educational system, would lead to a high productivity for large and small businesses. This in turn would result in a steady increase in employment, real incomes, and the most important ingredients of social security (such as guaranteed pensions and comprehensive health care).

This is exactly what happened, and a relevant question of late is whether a once magnificent welfare ‘structure’ that – for a number of years – was a source of envy for the residents of many countries, can be kept afloat if some of the most modern electric generating facilities in the world are scrapped for what are clearly short-term political considerations. For instance, in order to recruit voters with anti-nuclear tendencies, the recent Social Democratic prime minister informed those members of the population who prefer opinion and feelings to evidence and logic that nuclear power was “obsolete”. (Before continuing it should be emphasized that the relation between ‘socialism’ and Swedish social democracy is about the same as that between the words and music of a conventional rap standard and a Cole Porter ‘evergreen’.)

For some obscure reason, in l978 all the major political parties in Sweden agreed that the growing controversy over the future of nuclear energy should be settled by a national referendum. The electorate was subsequently asked to choose between nuclear acceptance, the more-or-less immediate closing of as many nuclear facilities as possible, or a gradual phase-out that was to be complete by 2010. Confronted by a whirlwind of neurotic fictions launched by a technophobic nuclear opposition, the latter option was selected. Although not fully comprehended by most Swedes even now, a key factor in that pseudo-scientific travesty was an assumption that the rising prosperity of Sweden could be maintained even if the country’s nuclear assets were liquidated. In other words, the choice between nuclear energy and ‘something-else’ was reduced to a matter of taste, and to add insult to injury, the country’s energy assets were pictured by many politicians as having little or nothing to do with the macro-economy, although in point of truth they have everything to do with it.

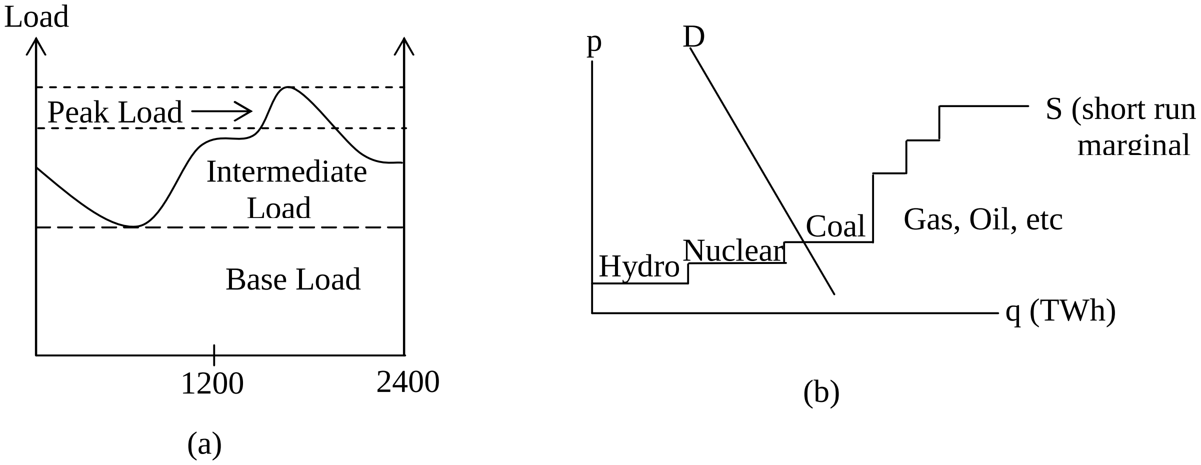
To a considerable extent, that ill-founded assumption is now passé, which is why a large majority of Swedish voters are no longer hostile to nuclear. In the UK, on the other hand, some polls indicate that many voters want to see nuclear and coal-based installations phased out in favour of renewables, while the government of that country is in favour of a nuclear revival. This is because, as former Prime Minister Blair once observed while commenting on some environmental considerations, without such a departure it will be impossible to achieve large reductions in carbon dioxide (CO_2). And not only Mr Blair. James Lovelock, a founder of Greenpeace, has surprisingly said that we do not need to fear nuclear energy, which he endorses as “the safest and most environmentally friendly source of that vital product, electricity.”

The difference between the two nations mentioned above where this question is concerned is that no country has made as great an effort to introduce renewables as Sweden, but even so the result in terms of the energy now being generated is slight. Consequently, as compared to UK residents, Swedes have gradually come to realize that while technically it is possible to substitute renewables for nuclear, the benefit-cost ratio is economically unacceptable.

Before going to some slightly more technical considerations, there is one aspect of the present debate about nuclear energy that everyone should consider. It turns on the expression *Capacity Factor* (CF), which has to do with the amount of energy that is actually produced over a given period as compared to the amount that could be produced if the facility had operated at maximum (or rated) output one-hundred percent of the time. This can be written CF = Actual Energy Output over a given period *divided* by Rated or *Maximum* Output. When you hear about the beauty of wind energy, ask about the Capacity Factor.

Consider for example a wind turbine that has a *power* rating of 100 kilowatts. In a month of 30 days its maximum *energy* output is 100 x 30 x 24 = 7,200 kilowatt-hours. However its *measured output* during that period would very likely be lower, and perhaps much lower. Suppose that it was 3,600 kilowatt hours. In that case we would have CF = 3600/7200 = 0.50 = 50%. As it happens, for wind a capacity factor of 20-35% is probably average. What about a nuclear installation? 30 years ago capacity factors in the U.S. were about 55% due to the ‘down-time’ caused by unscheduled outages and scheduled maintenance, but now outages have been reduced to where many reactors will have capacity factors above 85%, Also, if capacity factors are calculated *net* of scheduled outages, then occasionally capacity factors are about 95%, which apparently applies to plants managed by Exelon. Now let’s look at an important diagram:

Figure 1a is about the configuration of demand, with the story told on the basis of capacity. To be specific, the demand for electricity (or electric capacity) typically varies during a day in the cyclic pattern shown in Figure 1a. The *load* (on the vertical axis) is in kilowatts (kW), or megawatts (MW) or something of that nature (where ‘mega’ stands for millions). Here you can think in terms of the size and number of light bulbs in your residence, many of which are not on in the middle of the day, while all of them may be on in the



(a)

(b)

Figure 1

evening. We might say that demand 'peaks' in the evening.

On the horizontal axis in Figure 1a are hours, ranging from e.g. midnight to midnight – a 24 hour period. (Naturally we could have used a one month or one year period). Thus the 'box' that is designated "Base Load" is a portion of the *energy* that is expended during a 24 hour period, and this is measured in e.g. kilowatt hours (= kWh). The remainder of the energy for this period (in kWh) is the remainder of the area under this curve. Continuing with the light bulb example, you do not pay the firm that supplies you with electricity for the size of your light bulbs, but you pay them for the amount of electric energy you actually require and they provide, just as they pay the seller of e.g. coal or gas or 'uranium' for the items they use to produce electricity (and in which the energy resides in the first place). The base load here can be thought of as the load (in e.g. kW or MW) that is *always* on the line, while the peak load is the maximum load on the line, and which typically is in place for only a comparatively short period. A base load power plant is one that customarily provides a steady flow of power to a *grid* (i.e. a collection of power lines), and operates at all times except for unscheduled 'down-time' and scheduled maintenance.

Clearly, readers should not require any algebra to understand that the base load ought to be 'carried' by extremely reliable equipment. They should also add the expressions *base load* and *peak load* to their vocabularies as soon as possible, especially if they would like to participate in influential discussions on the present topic as an equal rather than an interloper. They should also take a few minutes to comprehend that we will not have much use for the highly stable demand curves that we deal with in our courses in microeconomics. One of this kind is shown in Figure 1b, and it unfortunately has a tendency to make appearances in important documents where it does not belong.

Many readers probably understand that if generating equipment is extremely expensive – as is the case with a very large nuclear or coal power plant – it cannot be an optimal arrangement to allow it to stand idle during most of the day in order to be available during the period when there is a peak load to be serviced. Conventionally, nuclear, coal, hydro and – since the introduction of combined cycle equipment – gas have been important for the base load, while gas and to a certain extent hydro have been important for the peak load. I have also heard it claimed that small *pebble-bed* reactors that may be constructed in the future that are capable of supplying economic peak-load power.

Fortunately, I was able to get some insight into the functioning of a hydroelectric installation when I was in the U.S. Army, and for a short time stationed near Yokohama in the vicinity of a small dam. One of the more interesting (informal) lectures I received on that occasion had to do with the unapparent flexibility of that facility, and just as interesting, the last time I visited Japan I was told that large dams are often capable of 'returning' well over than 50 times the energy invested in them – by which it is meant that if the money invested in constructing these dams were translated into energy units (which is a simple algebraic operation) and compared to the energy generated by these structures over their expected lifetimes, the ratio would be at least fifty. Only nuclear approaches this impressive result.

A Minimal Outline of the Nuclear Fuel Cycle

> "Satisfaction…came in a chain reaction."
> 'Disco Inferno' (from *Saturday Night Fever*)

In my courses on energy economics and international finance, I have made a point of informing students that there are certain things that I expect them to learn *perfectly* if they prefer a passing to a failing grade, and the same will apply to the items in this section the next time I teach energy economics. The reason is simple, and what it comes down to is the likely appearance of considerable new nuclear capacity (especially in Russia, the U.S., India, China and Japan) that deserves to be studied and understood by persons who may find themselves in position to influence the configuration of the energy structure in their country or their local community, or for that matter merely to comprehend and explain some aspects of nuclear energy to friends and neighbours. There will also be new capacity in localities where politicians and their foot soldiers have repeatedly taken what amounts to a sacred vow to never think about or build or tolerate the construction of another reactor, because once TV audiences fully grasp what the lack of abundant energy will mean for them *personally,* an accelerated reassessment of the nuclear option will likely take place.

It is often said that the world's first 'nuclear reactor' – which in reality was an experimental device of a very primitive sort whose function was to obtain the first man-made sustained nuclear reaction – was constructed by Enrico Fermi. This took place in the squash courts under the stands of the football stadium at the University of Chicago. That charming stadium had been removed from the great world of (American) football because the University's president regarded the sport as inconsistent with the intellectual grandeur he desired for the institution over which he had unfortunately been granted authority.

The first peacetime nuclear plant was used to power the U.S. submarine Nautilus – although some observers preferred the label 'wartime extension' to 'peacetime'. This was in January 1954. Six months later the Russians constructed a small nuclear-based installation whose purpose was to supply power to non-military users, and in October 1956 the first full-scale nuclear plant for civilian use was opened at Calder Hall in the UK. The first genuine 'civilian' power plant in the U.S. began operation in l958 at Shippingport, Pennsylvania. Perhaps the most interesting event during that phase of the Cold War however was the launching of the submarine USS Sea Wolf in l956, which contained a liquid-sodium cooled breeder reactor of the type that Ralph Nader once referred to as "maniacal". The 'breeder' will not be given much attention below, but it can be emphasized that its performance differs greatly from the light-water reactors (LWR) that form the major part of the U.S. nuclear inventory. Light-water reactors tend to feature two models: the boiling water reactor (BWR) and the pressurized water reactor (PWR).

We can now turn to the simple physics of nuclear energy. Energy produced from fossil fuel is the result of an uncomplicated chemical process, however energy produced from nuclear fuel originates in the force binding the constituent parts of the fuel's atoms together, and its release features the alteration of the structure of the atom itself. This is probably one of the reasons why the Nobel laureate Professor Dennis Gabor called the nuclear reactor the most important scientific achievement of all time. There may be some question as to whether it deserves that spectacular designation, but in many respects it is the most sophisticated.

Two terms probably already found in the vocabularies of readers of this exposition are molecules and atoms, but they should be reminded that the latter is essential when examining the present topic. The expression molecule was coined by René Descartes in the 1620s, by which he meant an extremely minute particle: for the most part molecules cannot be seen with the naked eye, although apparently there are exceptions. Molecules are made up of at least two kinds of atoms in a definite arrangement, held together by strong chemical bonds. For instance, the water molecule is composed of hydrogen and oxygen atoms, and designated H_2O. Atoms are generally thought of as 'indivisible', or the smallest particles characterizing a chemical element, but in reality sub-atomic particles have been identified.

Almost all of an atom's mass is found in its nucleus, which contains neutrons and (positively charged) protons, surrounded by swarms of (negatively charged) electrons, and the larger this nucleus, the easier it is to obtain the desired release of energy. Uranium is so important because one of the heaviest (and most complicated) atoms in nature is the *isotope* 235 of uranium, which is the only *naturally occurring* nuclear 'fuel' that will support a chain reaction. Its conventional designation is U-235, and it is important to know that different isotopes of an element occupy the same position in the periodic table, but they do not have the same weight. U-235 contains 235 'particles', with 92 protons and 143 neutrons. The other isotope of uranium is U-238, with 92 protons and 146 neutrons. (The difference in weight is attributable to the neutron difference.)

Fission is the breaking apart of a nucleus following the absorption of a neutron. If U-235 absorbs one additional neutron, it can become unstable and divide into two or more 'fragments' (sometimes called "atomic nuclei"), in addition to several neutrons. The mass of these fragments and neutrons is now somewhat less than that of the original nucleus and, most importantly, the reduction in mass corresponds to an increase in kinetic energy (i.e. motion), which is converted into heat as the fission products collide with surrounding atoms. Other U-235 atoms may absorb the neutrons released by a previous fission and themselves undergo fission. A release of neutrons that leads to further fission constitutes a "chain reaction". What we have here is a mass-to-energy conversion of the kind associated with Albert Einstein's famous equation $E = mc^2$, where m is mass, c is the speed of light in a vacuum and E is energy. This equation specifies that the amount of energy that can potentially be released by only a small mass is huge.

A complication however is that once a chain reaction develops, some sort of control is necessary to ensure that it continues at a steady level: sufficient but not too many neutrons must be obtained, and they must move at the right speed. On average this means that one neutron should lead to *only* one more fission. What is *not* desired is an *uncontrolled* exponential growth of fissions, which in the worst of cases could result in a *meltdown,* i.e. an overheating of the reactor core, or even an explosion. (It can also be noted that the neutron – discovered in l932 by James Chadwick – is the key to nuclear fission, because as a result of being neutral, it is not repelled by 'Coulomb' forces associated with atoms.)

Occasionally we hear the expression *critical mass* in the discussion of this process. (This is also used in socio-dynamics, where it means the existence of sufficient momentum in a system so that the momentum becomes self-sustaining and fuels further growth. 'Bandwagon effect' was an expression that was popular when I studied economics, and it had to do with a kind of (social) critical mass.) It is important to appreciate that U-235 is fissile, but not U-238, however it is equally crucial to recognize that U-238 is *fertile*, which means that it can be the source of fissionable material not found in nature if it is bombarded with neutrons in a reactor. That material is plutonium (Pu, or Pu-232). Another fertile element is thorium, which may be as abundant in nature as uranium, and can also be made fissile via neutron bombardment in a conventional reactor.

Natural uranium consists of 99.3 percent U-238 and only 0.7 percent U-235, where by 'natural' it is meant ore *or* refined uranium with the same isotopic composition that is found in nature. (There is a slight approximation here because there is a minute quantity (or 'trace element') of U-234 in natural uranium that is always ignored when discussing fission.) The relatively small amount of U-235 introduces a complication into obtaining a chain reaction, because enough enrichment must usually take place to raise the amount of U-235 in reactor fuel to at least 3%. At the same time it should be understood that there are reactors – such as the Canadian CANDU reactor – where unenriched natural uranium is an input. What characterizes this equipment is a thorough removal of non-uranium impurities, which together with the employment of suitably designed neutron reflectors and a *heavy-water moderator* can provide a chain reaction. Although enrichment is a very costly activity, there does not seem to be any evidence that (economically) CANDU and similar reactors are superior to light water equipment, apart from CANDU managers not having to worry about an unexpected spike in the cost of enrichment, which is a discomfort that LWR managers might suffer if their enrichment takes place externally.

The term ‘moderator’ used above has to do with reducing the speed of neutrons, so that the main source of energy is the break-up of heavy fissionable atoms that are struck by relatively slow rather than fast neutrons. Often the moderator is water or gas, but in the CANDU it is heavy water, which means water containing deuterium atoms. By way of contrast, the breeder is often called the ‘fast breeder’ because the neutrons are not slowed down (between fissions), and given the fuel (Pu), it is technically much more efficient. According to Barre and Bauquis (2007), a kilogram of natural uranium in a breeder can provide almost 100 times more energy than it would in a conventional reactor.

Now for a brief resumé of the nuclear fuel cycle. The *front end* begins with mining. (Australia, Kazakhstan and Canada have the largest uranium reserves). This mining is not as straightforward as it sounds, because the *ore* that is mined usually contains well under 1% uranium. In its pure form uranium is a silver-gray metallic chemical element that is approximately 70 percent more dense than lead (and weakly radioactive), and this metal can be obtained by crushing and grinding the ore. However, since there is relatively little demand for the metal, it is usually sold in the form of yellowcake (or U_3O_8), which is still classified as natural uranium. In A.D. Owen’s seminal book on the economics of uranium (1985), he points out that one tonne (= 2204 pounds) of uranium metal (U) corresponds to 1.18 tonnes of yellowcake (U_3O_8). Thus, for every dollar per pound paid for yellowcake, an average of 1.18 dollars is paid for uranium metal.

To obtain yellowcake, further processing in the form of milling and leaching (with sulphuric acid) must take place. Yellowcake is generally classified as the basic raw material for fission fuel, and it is the price of yellowcake that is relevant when the price of ‘uranium’ is discussed in the trade literature. Yellowcake is then converted into uranium hexafluoride (UF_6), which is heated into a gas that is suitable for enrichment.

As noted above, the purpose of enrichment is to increase the percentage of fissionable U-235 in a bundle of uranium from approximately 0.7 percent to about 3 percent, or perhaps slightly higher. (The higher the degree of enrichment, the easier it is to maintain a chain reaction, and so the volume of the reactor can be reduced). There has been a great deal of talk recently about certain countries taking enrichment to a point where they can obtain weapons-grade uranium, which means enrichment to about 93% U-235.

All enrichment is a very complicated (i.e. expensive) process, however its technology has been greatly advanced by moving from gaseous diffusion to the centrifuge system, and further improvements are almost certainly possible. Once UF_6 is obtained, a further conversion into uranium dioxide (UO_2) takes place, and this is fabricated into pellets. The pellets are loaded into specially designed tubes. In a light water reactor the rods are inserted into the reactor where fission takes place, and the ensuing heat raises steam in a boiler which turns a turbine-generator that produces electricity. From the boiler to the back end of the cycle a nuclear power plant is the same as a plant operating on coal or gas, with approximately the same thermodynamic characteristics.

When a reactor has been in use for a certain period, the percentage of U-235 in it has decreased, and because of this and the contamination of the fuel elements by fission products, the efficiency of the chain reaction is reduced, and eventually it cannot be sustained. *Spent fuel* is then removed from the reactor and ‘fresh’ fuel inserted. The depleted uranium is called *tailings*, and is mostly U-238. It cannot be used in ‘slow’ reactors, but if put in e.g. breeder reactors and exposed to high energy electrons, it can be converted to fissionable isotopes of plutonium. (This expression ‘tailings’ is also sometimes used to describe the large amount of ore that remains after the crushing and grinding that takes place in order to obtain uranium metal.)

A peculiarity with the cycle discussed above is that, theoretically, it is incomplete. The spent fuel that is taken from the reactor is usually stored, however instead it could be reprocessed and in one form or another fed back into the reactor, thereby completing the cycle. If this is not done, what we have is a *once-through cycle*, where the spent fuel is put into temporary storage, and kept there until consigned to permanent storage – preferably underground. *Put another way however, this spent fuel is not 'waste' – which it is often called – but potential reactor fuel, because it contains an impressive amount of fissionable materials.* Were it not for various political and environmental constraints, a larger amount of it would be turned into plutonium (which could be directly used in a breeder reactor) or a plutonium-laced mixture called MOX (mixed-oxide fuel) for reinsertion into modified conventional reactors. Perhaps the main bugaboo is that reprocessing involves the handling or availability of a relatively large amount of plutonium, which is a substance whose presence in large quantities is not to be recommended if our political masters deal with this commodity the same way that they often treat other potential menaces.

By way of winding up this part of the exposition it should be noted that two terms that often appear when the conversation turns to reactors are *thermal reactors* and *fast reactors*. Both require a fissionable fuel, which for a fast reactor can mean Pu-239 as well as U-235, and both require a coolant to counteract the heat that is created as a result of fission. Thermal reactors also require a moderator to slow down neutrons, as well as various components to ensure that the fission is controllable. The fast reactor also requires a mechanism for control, but it is very different from that employed in a thermal reactor. These are a few other rather special items that could be taken note of, especially if the fast reactor is also a breeder (i.e. creates more fuel than it uses), but these cannot be discussed in an overview of this nature.

Some Analytical Extensions

Readers of this paper should now be in possession of sufficient terminology to convince friends and neighbours that they have something useful to offer when the discussion turns from jazz or Frank Sinatra to nuclear energy, and for persons who feel at ease with the topic, the present section should greatly enhance their knowledge of the subject. Particular attention should be paid to equation (2) below, even if the algebra before and after this relationship causes a problem. The items that will be taken up below are the capital cost of nuclear, followed by an output-input analysis that concludes with the so-called '*burn-up*' (which has to do with the efficiency of using uranium), and finally, I want to discuss with a few equations a contention I have made in many lectures and informal conversations about the comparatively low cost of nuclear electricity. To be exact, since Sweden and Norway may still produce the lowest cost electricity in the world – although Norway employs almost exclusively hydro, and Sweden nuclear and hydro – some algebra shows that Swedish nuclear has about the same low cost as Norwegian and Swedish hydro. (Note: *the lowest cost* although all the buyers of this electricity may not always enjoy the lowest price. One of the reasons for this is the Swedish entry into the European Union, which has facilitated the export of electricity.)

We can start with what I hope is a useful example. This involves a two year situation in which \$1000 is borrowed and used to invest in an asset, for example, a mini-reactor that will be placed in the basement of your house, and which will be amortized in two payments over (an amortization period of) two years. The rate of interest (or the discount rate) in this example will be taken as 10% (or 0.10). (Amortization means repaying a debt, which in this example is tied to the purchase and cost of a reactor.) It is here that we introduce the term *annuity*, which is the amount (A) paid at the end of every period (i.e. year), and as will be calculated below, the annual amount 'A' is equal to \$576. This means that in repaying the debt (=\$1000), we pay \$576 at the end of the first year, and also \$576 at the end of the second year. Observe also that the debt 'today' is \$1000, and if paid at the end of two years, the lender would receive F = PV$(1+r)^T$ = $1000(1+0.1)^2$ =1210 dollars if 10% is the rate of interest. Let's put this as follows: F in T years is equivalent to PV today.

Let's look closer at this. There is a payment of $576 at the end of the first year, and this is equivalent to 576 (1+0.1) = $633 at the end of the second year. If we add this to the annuity payment of $576 at the end of the second year, it sums to approximately $1210, or the same as above. It can thus be specified that, *ceteris paribus,* paying $1000 now for the asset, or paying $1210 at the end of two years, or paying $576 at the end of the first and second years are (in theory) equivalent, given that 10% is the applicable rate of interest.. Note the *ceteris paribus* criterion, because obviously in real life there are situations where this 'equivalence' would not be accepted, particularly by a lender.

Something else that can be mentioned is that if the reactor had been paid for in cash removed from your wallet or purse at the time it was purchased, rather than borrowing to make the purchase, the concept of an annuity would still be valid. In this case the annuity payments represent the *opportunity cost* of purchasing this asset instead of e.g. lending the cash today and earning interest (amounting to e.g. $210 after two years).

Now let's generalize this two period example to T periods. Two equivalent arrangements for paying a debt of PV (called the *present value*) that is entered into at the beginning of the first period is to pay PV$(1+r)^T$ (= F) at the end of T periods, or via annuities 'A' at the end of each period (e.g. year), beginning with the *end* of the first period, and ending at the end of the last period! Thus we can write:

$$PV\,(1+r)^T = A + A(1+r) + A(1+r)^2 + \ldots\ldots.. + A(1+r)^{T-1} \qquad (1)$$

This is a key expression, and if the reader has any problems here, he or she should work with the two period example given above. Next, multiplying both sides of this expression by (1+r) we obtain:

$$(1+r)[PV(1+r)^T] = A(1+r) + \ldots\ldots\ldots + A(1+r)^T$$

We continue by subtracting the second of these expressions from the first:

$$[(1+r)^T]\,PV[1-(1+r)] = A - A(1+r)^T$$

From this we obtain equation (2) below, which turns out to be:

$$A=\left[\frac{r(1+r)^T}{(1+r)^T-1}\right]PV \qquad (2)$$

If we make PV = 1000, r = 0.10 and T = 2, then we can calculate A = 576, as noted above. 'A' is generally referred to as 'levelized cost' in most of the technical literature relating to nuclear energy: it is the periodic payments for a reactor costing PV. This very important expression can also be derived using elementary calculus, beginning with a fundamental (neo-classical) economics concept: the capital cost of an investment can be defined as the uniform return per period that an asset must earn, in order to achieve a net present value of zero. In other words, the asset price is the present value of future net yields (i.e. revenues minus costs). Notation in this derivation is changed somewhat in order to correspond to standard usage. Taking I as the asset price (i.e. where I is specifically designated the investment cost, instead of PV as in the above equation), P the capital cost per period, and r the market discount rate, we can write for T periods:

$$I=\int_0^T Pe^{-rt}dt = \frac{P}{r}\left(1-\frac{1}{e^{rT}}\right) \qquad (3)$$

It takes very little manipulation to obtain P = $re^{rT}I/(e^{rT} - 1)$. Remembering that we can approximate e^{rT} by $(1+r)^T$ for small values of r, we obtain equation (2), though here 'I' is used rather than PV (and P instead of A), although in both cases we are talking about an investment cost. The discount rate employed is the market interest rate, because in the great world of neo-classical economics, there is usually no risk/uncertainty on the part of lenders and borrowers, which means that the risk-free interest rate is appropriate. This is not the kind of recommendation that needs to be taken seriously outside a seminar room. Note also that if the final value (F) of an investment is related to the present value by F = $PV(1+r)^T$, this expression would yield for the present value PV = $F/(1+r)^T$. For example, 1000 = $1240/(1+0.1)^2$. What has been done here is to *discount* F.

We can proceed with output-input analysis of electricity production with a nuclear reactor, beginning with the observation that based on its atomic structure, 1 gram of pure U-235 can produce 0.9 MWd (= 0.9 million watt-days = 0.9 megawatt days) of *energy*, and so the amount of U-235 necessary to produce 1 MWd of energy is 1.1 grams, assuming that the fuel is completely fissioned in a perfect reactor – i.e. a reactor without heat loss. (An example is in order here. Suppose that you have an ideal reactor in your basement that is fuelled with 1.1 grams of pure U-235, and ten 100 watt bulbs (= 1000 watts) are burning all day every day in your humble abode. Then you can keep your house shining brightly for 1000 (= 1,000,000/1000) days, where the units here are watt-days/watts = watts. Incidentally, 1 gram = 0.0022 pounds, which is a number that will be useful later on).

But heat loss is a thermodynamic fact of life, and so in order to get 1 MWd(e) of *electric* energy we might need e.g. 3 MWd (thermal), where thermal relates to the fuel being used, which in this case is uranium. Accordingly, with one giga-watt (e) = 1 GE(e) = 1000 MW(e) operating over a year on the output side, our U-235 requirement on the input side is 3000 x 0.85 x 365 x 1.1 = 1,023,825 grams, where the assumption for this example is that the capacity factor – the fraction of a year that the reactor is actually operating – is 85%. Note again the difference between MWd (energy) and MW (power).

However heat loss is not the only bad news here, because the fuel that is inserted into a reactor is *not* pure U-235, as was indicated earlier in this paper. Instead it is a bundle of U-235 and U-238 that has been enriched from 0.7% of the former to at least 3%. As noted earlier, an item on the positive side is that some of the U-238 was converted by electron absorption to Pu-239 and fissioned, but this process is slower than the fissioning of U-235. It thus turns out that to complete our work we require a technological parameter that will tell us about the efficiency of utilization of the (enriched) uranium fuel – i.e. fuel containing both U-235 and U-238 – and this is called the *burn-up. The burn-up is the total amount of heat energy created per unit of uranium fuel (i.e. enriched uranium*)! In economics this would be called an input-output coefficient. A figure that I recently saw is 33,000 MWd per tonne (which corresponds to 33,000 x 1.1 grams (of U-235) per tonne of (enriched) uranium fuel).

Using the previous calculation we get for the annual use of uranium by the reactor in order to generate 1000 MWd(e) the quotient [3000 x 0.85 x 365 x 1.1/ 33,000 x 1.1] = 28 tonnes of enriched uranium. The input-output character of this calculation is best seen by forgetting about the uranium equivalencies that came into the picture with the use of the number 1.1, and simply noting that the MWd(thermal) input in order to obtain 1000 MWd(e) for a period of one year is 3000 x 0.85 x 365 MWd divided by 33000 MWd per tonne, and once again the answer (= 28) has for units *tonnes* (where 1 tonne = 1t = 2204 pounds). Remember that this 28 tonnes is enriched uranium, and so it might be possible to propose another input-output relationship between enriched and natural uranium. As far as I can tell, 28 tonnes of enriched uranium corresponds to about 150 tonnes of natural uranium, and so the input-output coefficient is six.

The next step will be to use equation (2) to calculate the capital cost and the energy cost of nuclear for an interest rate of 5%, an investment cost (PV or I) of $2500 per kilowatt of capacity, and for two values of T: 30 years and 60 years. With T = 30 years, the levelized cost of a kilowatt of *capacity* is \$162.5 dollars per year for 30 years, as calculated from equation (2). If we are interested in the energy cost, and the capacity factor is e.g. 0.85, then the amount of energy produced in a year by *one kilowatt* is 24 x 365 x 0.85 = 7446 kWh. The energy cost is then 162.5/7446 = \$0.022/kWh. Now suppose that T =60. The levelized capacity (or capital) cost becomes \$131.25/kW, while as a component of energy costs is \$0.017/kWh. (The fuel cost will be taken up in Section 5).

Clearly, as T increases, the capital cost decreases. I chose 30 years to begin with because that is the value often seen when discussing the 'life' of nuclear facilities, but it happens that reactors are being constructed with an expected life of *at least* 60 years, and the lives of older reactors are being extended by upgrading. As for the interest rate, if the world functioned the way that I believe it should function, then the government would serve as a guarantor for amortization payments, and 5% would be a suitable interest rate to use in calculations of the type discussed above.

The last exercise in this section involves a statement about the relative cost of nuclear, where relative means that it will be compared to hydro – which is the most inexpensive generator of electricity. Moreover, according to data that is easily available in the Stockholm School of Economics (and elsewhere of course), the (average production) cost of electricity in Sweden, which involves hydro (H) *and* nuclear (N) is about the same as the average cost of hydro generated electricity in Norway. (The price to consumers may or may not be the same, which is irrelevant for the present discussion). Calling Sweden country 1, and Norway country 2, the following algebra seems appropriate, noting that C'/q' represents average cost:

$$\frac{C_{1N} + C_{1H}}{q_{1N} + q_{1H}} = \frac{C_{2H}}{q_{2H}}$$

This can be written in the following manner, where q is the total output of electricity in Sweden:

$$\frac{q_{1N}\left(\frac{C_{1N}}{q_{1N}}\right) + q_{1H}\left(\frac{C_{1H}}{q_{1H}}\right)}{q} = \frac{C_{2H}}{q_{2H}}$$

Both sides of this expression can now be multiplied by q, and in addition q_{1N} can be taken as θq and q_{1H} as (1 – θ)q. Using these in the above expression we are then able to write the above expression as

$$\Theta q[C_{1N}/q_{1N}] + (1 - \theta)q[C_{1h}/q_{1h}] = q[C_{2h}/q_{2h}]$$

The q's can be cancelled, and making the reasonable assumption that $C_{1H}/q_{1H} = C_{2H}/q_{2H}$, some simple manipulations will give us:

$$\frac{C_{1N}}{q_{1N}} = \frac{C_{2H}}{q_{2H}} \qquad (4)$$

What this says is that the average cost of nuclear generated electricity in Sweden is equal to the average cost of hydro generated electricity in Norway, which in turn is probably the lowest cost electricity in the world.

Finally, the price of uranium (fuel) is a topic that requires an extensive discussion, but while that discussion is comparatively simple, it will have to be provided elsewhere, because it would require too much space in this paper. It can be mentioned though that the price of yellowcake reached an all-time low of $7/pound (= $7/#) in 2001, while today it is approaching $80/#. Even so, the students of this topic have expressed no alarm. They know – as I know – that when uranium becomes scarce the breeder reactor will have its opportunity. Comments on this prospect will be left to others, because I feel no enthusiasm for the plutonium economy.

More Background for Curious Readers

One of the most brilliant appendages to the topic that we are discussing can be found in a non-technical article by the late Samuel Schurr (1988). Concentrating on the United States, Schurr demonstrated that the total energy use in what he termed the "business sector" more than doubled over the period 1920-73, and in relation to capital (= machinery + structures) increased by 50%. The observed slight fall in the energy intensity of *output* was then shown to be due to technical change (largely motivated by increasingly energy intensive *inputs*) raising output by so much that, *percentage-wise*, output increased by more than energy consumption. (It was due to the failure to understand the details of this phenomenon that many concerned observers found themselves confronting and often elaborating on the bogus argument that output could be maintained or for that matter increased even if the input of energy declined.) Schurr also hypothesized that electrification meant a flexibility in industrial operations that would have been impossible with any other form of energy, and this was the cardinal reason for productivity growth. Equally as important, electricity would play an indispensable role in the employment of items such as computers, whose revolutionary promise was just being realized.

If this is the actual situation, then an intelligent economist living in complete isolation from the 'real world' – which, unfortunately, is a world in which security problems cannot be ignored – might suggest that the best strategy for fostering economic growth, as well as stabilizing or reducing atmospheric greenhouse gases, is a *massive* program of nuclear construction, and it should be commenced as soon as possible. This humble commentator is definitely in favour of more nuclear, but at the same time it seems appropriate to wait until security problems assume another dimension before anything resembling a "massive" commitment is undertaken. In addition, it needs to be emphasized that an optimal energy 'package' for any region probably contains a very large component of renewables.

A country that illustrates to some extent the last observation is of course China. In 2007, 3.4 gigawatts (= 3.4 GW = 3.4 billion watts) of wind-based capacity was added to China's electric grid, while by 2020 the desire is to raise nuclear capacity from its present 10 GW to 40 GW, which is the fastest proposed increase in the world. Similarly, the intention is to add 1300 GW to China's total electric generating capacity by 2020 (which can be compared with the total present U.S. capacity of 1000 GW). Unfortunately, however, regardless of the amount of nuclear, wind and solar that the Chinese deploy, a large amount of coal will almost certainly be consumed. A question that should therefore be asked the anti-nuclear booster club is would they like the government of China to cancel its nuclear and hydro programs, because this would result in an even greater increase in the output of carbon dioxide generated in that country.

The problems brought about by coal have been touched on briefly in my textbooks and also my book on coal (1985), but this is an issue that requires a great deal of consideration, because despite increased concern over global warming, it is very unlikely that the growing world population will ignore the energy in that commodity. An important discussion of coal in Europe that applies to other regions can be found in a short paper by Jeffrey H. Michel (2008), and in a personal communication Michel informed me that "Carbon Capture and Storage (CCS) would effectively bury a third of usable energy resources underground and consume twice the water of conventional power generation, making its wide-scale implementation doubtful." Although it cannot be taken up here, the Swedish utility Vattenfall used the increased profits made possible by electric deregulation in Sweden and open borders in Europe to raise electricity prices in Sweden, and also to expand their coal producing operations in Germany. Despite assurances to the contrary, this latter commitment will not have anything to do with reducing CO_2, since it will focus on increasing Vattenfall's record profits, with the blessing of the Swedish government.

Observing the Swedish nuclear past provides a valuable but generally unappreciated insight into mechanics and digressions of what Professor Ken-Ichi Matsui (l998) calls the "Seventh Energy Revolution", which he believes will be based on nuclear energy. This is so because In Sweden natural gas has often been singled out as one of the main replacements for nuclear. As alluded to earlier, the main advantage of nuclear as compared to gas based equipment was in the cost of the fuel, which meant that gas was at a disadvantage for carrying the base load, although the capital cost of a nuclear facility was much greater. When, however, combined cycle gas-burning equipment became widely available, and in addition the price of gas fell, it was claimed by persons who should have known better that gas would *always* be much more economical than nuclear (for generating the base as well as peak loads). With the price of gas in the vicinity of 3.5 dollars per million Btu (= $3.5/mBtu), it was easy to insist that gas was a better economic bet than nuclear, and a locale where this was argued at great length was California..

In Sweden, if an accurate (and comprehensive) calculation had been made, if notice had been taken of what was taking place in the rest of the world, and especially if there was less technofobia in and around the political establishment, the claims made about gas would have been openly ridiculed, because it has long been obvious to many of us that the infinite supply of gas that many so-called energy experts were thinking of was actually finite – as everybody is either finding out or will soon find out; and since environmental considerations dealing with CO_2 were becoming more important, nuclear displays am indisputable social cost advantage over gas. Here I can mention that a few years ago, when the cost of gas first touched $7/MBtu, many predictions from highly reputable sources claimed that it would reach $10/MBtu by 2012. In point of truth, the price of gas should reach that level before the present year is out, and since there will still be a large gap between the BTU price of oil and gas, the price of gas will almost certainly continue to rise. Readers who want an up-to-date examination of the prices of energy resources should turn to the site '321 Energy', which can be reached via GOOGLE. They will also find on that site a large collection of non-technical articles published in the international press.

Another example might be useful here. The first time that I taught in Australia it was widely advertised that the Maui gas field in New Zealand was virtually inexhaustible. The reserve situation is quite different at the present time, however that field is still spoken of as being extremely valuable. *Not*, it should be emphasized, for producing natural gas, but for storing – or 'sequestering' as they say – as much as possible of the CO_2 that will be generated in the coal-based generating facilities that will eventually be required in this century to provide New Zealand with an increasing fraction of its electricity. It can also be mentioned that the New Zealand electricity deregulation, which at one time was praised as the most satisfactory in the world, was very likely based on beliefs about the availability of gas that were completely illusory. I suspect that this was an important factor in establishing a natural gas price for that country that was probably lower than what in economic theory is sometimes termed the 'scarcity price' (or the theoretically correct market price).

According to Torsten Gustafson, chief scientific advisor to the Social Democratic government of Tage Erlander, there was a positive attitude toward nuclear energy in Sweden until about 1970. After that time, two of the five major political parties in Sweden – the 'farmer party' and the communists – came to the loopy conclusion that the 'friendly atom' was bad for Sweden and just about everyone else, although there were a number of opponents to nuclear energy in all political and social factions. There is no rational explanation for the strong aversion developed by any political grouping to nuclear energy, since e.g. farmers and industrial workers were clearly important benefactors of inexpensive electricity.

This situation could probably be compared to something like the 'tulip *bubble'* in Holland in the 17th century, when intelligent people suddenly and inexplicably discerned enormously valuable qualities in the humble tulip, and paid fantastic prices for a commodity that eventually turned out to have no commercial and little intrinsic worth. The commodity in the present case is the belief in nuclear disengagement, which might provide a large slice of the voting public with a tangible psychological satisfaction in the short run, but in the long run would deprive Swedish industries and households of the comparatively low-priced access to an indispensable input.

The final topic in this section is the almost unknown concept of the so-called 'backstop technology', which as outlined by William Nordhaus in a brilliant article (1973) is the technology used to exploit a resource or asset that will still be available when all or most of the conventional resources are history. Not much is heard of the backstop these days, and I doubt whether I mentioned it in my energy economics textbooks, but there was a time when – in my lectures – I always brought it up in the context of discussing nuclear energy, although unlike Professor Nordhaus I treated it as a means for supplying the 'extra energy' need to produce motor fuel or energy liquids from biological resources. For instance, although not widely known, Sweden possesses large quantities of low-grade uranium, and eventually science and technology will make it feasible to utilize these resources in a politically and environmentally approved manner. As a result, they might make an impressive contribution to the Swedish economy.

For the purposes of this exposition, a backstop is a known technology for producing a very large amount of a given resource at a known price. (Actually, Nordhaus thought in terms of an infinite amount.) Suppose for instance that at a certain time only coal was used to produce electricity, but there is only a limited amount of coal in the crust of the earth. When, however, this coal is exhausted, we will still desire electricity over a very long time horizon, and so it is necessary to think about an alternative technology for producing electricity that is more than a 'stopgap'. One candidate might be uranium and thorium burned in breeder reactors, because given the likely amounts of these resources, they would be capable of producing electricity for many decades, or even centuries. Please note though, that this is NOT an advertisement for the breeder.

A different example that might be useful is oil from coal functioning as a backstop for conventional crude oil. As is well known, there are technologies available that can provide large amounts of liquids that can fulfil the present functions of crude oil. (Observe that I said large but not, as Nordhaus, an infinite amount.) A trivial example will now be formulated for the purpose of obtaining a not very profound result, but one that needs to be spelled out in the light of what is happening at present on the oil market.

Suppose that crude oil is finite in supply, with B units available until the global supply peaks, and this oil can be extracted at zero (marginal and average) cost. Moreover, every year A units are extracted. This means that, *ceteris paribus*, it will be possible to extract oil for $T = B/A$ years until its output inexorably begins to fall. Thus, at the end of T years, if we want to continue enjoying A units of oil, *or an oil equivalent*, we must have a supplementary technology available that will allow us to produce the difference between A and global output Q, whatever that turns out to be.

To keep things simple, suppose that this 'peaking' amounts to a decline in output to Q, at which level it is believed that it will be maintained, and with $X = A - Q(T)$. Suppose also that the technology that will allow us to produce X units of oil indefinitely will cost Z dollars.

Its cost today, at time't', is thus $Ze^{-r(T-t)}$, where r is an interest rate. In other words, if we put this amount in a bank, and the interest rate was 'r'. Then in (T – t) years it would grow to Z, and we would be able to purchase this technology. The next step is elementary. If the technology costs Z, and we desire A units, then the cost of obtaining one unit of this oil is Z/[A – Q(T)] = Z/X = F, or what is the same F(T). Since we said that at present oil can be extracted at zero cost, if it were not for the exhaustibility of the resource the present price would be zero, but instead we must remember the need to purchase a new technology in T years, and so the (theoretical) oil price at the present time is $p(t) = F(T)e^{-r(T-t)}$. In a perfect world the market would provide this price.

When I began teaching energy economics, T was far, far away. Now there are people who believe that it is no more than a few years in the future. In a perfect textbook world we would know exactly when T would arrive, and take steps to ensure that we had the oil needed to ensure that every winter we could make our way to the skiing and partying in the north of Sweden. For instance, in terms of the discussion above that involves Sweden, it would mean having reactors that could supply the extra energy needed to produce e.g. synthetic oil.

A little calculus will show that if more oil was found, the time when synthetic oil would be required would be pushed further into the future, and so p(t) would be smaller. It is also possible at the cost of some complication to solve this problem for an arrangement where the decline in Q after T years is not in the form of a step function, but instead takes on the form of the 'tail' of a normal distribution. I prefer to leave these extensions to someone else, while stressing that in a world in which the peak oil hypothesis is gaining increasing support, an increase in the price of oil and the increasing respectability of nuclear energy makes all the economic sense in the world.

Some Aspects of Nuclear Costs

One of the assumptions in my new textbook is that even if natural gas were available at bargain-basement prices (which is no longer likely), it would be sub-optimal to regard it as preferable to nuclear where new investments are concerned. The global output of gas might peak in twenty or thirty years, while a new nuclear installation will be on line for at least 60 years, and could still have access to *comparatively* inexpensive uranium. The peaking of gas during the lifetime of nuclear installations constructed e.g. today will increase the opportunity cost of that resource in such a way as to make it extremely difficult to comprehend why, in a highly literate country like Sweden, where as in the rest of the world the relative value of money is steadily increasing, it has become possible to consider it a replacement for nuclear.

An important discussion of the cost of energy resources can be found in Chapter 8 of Barre and Bauquis (2008). The *Economist* (July 9, 2005) has presented estimates from several sources for average electricity costs. For German utilities the Union Bank of Switzerland (UBS) gives 1.5 cents/kwh for nuclear, 3.1-3.8 cents/kWh for gas, and 3.8-4.4 cents/kWh for coal. Similarly, they give 1.7 cents/kwh for nuclear in the US, 2 cents/kWh for coal, and 5.7 cents/kWh for gas. The International Energy Agency (IEA), employing a discount rate of 5%, argues that nuclear is \$21-31/Mwh, while gas ranges from \$37-60/Mwh.

Other sources (e.g. Massachusetts Institute of Technology (MIT) and Britain's Royal Institute of International Affairs) seem to disagree with these figures, but in a summary of generating costs originating with the International Energy Agency (IEA) and OECD, Tarjei Kristiansen of Statkraft Energi AS (Norway), claimed that with a 5% discount rate, generation costs in \$/MWh are 23-31 for nuclear, 25-50 for coal, and 37-60 for natural gas, More research needs to be done on this topic, and it is true that just now uranium prices are rising, however many uranium mines are being reopened.

Results such as those given above should be taken with a grain of salt because movements in exchange rates might lead to the wrong conclusions. However in the calculations of capital and energy costs above I used a burnup of 33,000, but I recall Professor Ulf Hansen of Rostock University saying that the average burnup now might be between 45,000 and 50,000. If this is true, and at the same time all countries could construct nuclear facilities in 4 years – which the Japanese have shown to be possible – and the life of a new nuclear installation is at least 70 years, which I regard as certain, then nuclear energy is the optimal medium for carrying the electricity base load.

According to estimates of the World Nuclear Association in 2000, the country with the largest uranium reserves is Australia, whose reserves at that time were 622,000 metric tons (= 622,000 tonnes = 622,000t), and whose production was 7,720t. In what follows I would denote this as (622,000; 7,720). This discrepancy seems very large, but not when I remember the negative attitudes toward the production of uranium by my mathematical economics students in Sydney and Melbourne: they were definitely not interested! The largest producer was Canada, with a production of 12,520t and reserves of 331,000t = (331,000; 12,520). Other important countries were Kazakhstan (439,200; 2018), Namibia (156,120; 2,239), Niger (69,960; 3,095), Russia (145,000; 2,000), United States (110,000; 1000), Uzbekistan (66,210; 2,400), other (306, 940; 2774). Total estimated reserves in 2000 were thus 2,246,430t, while production was 35,767 tonnes. For technical details see Owen (1985), but the total input of uranium in e.g. the production of electricity exceeds 35,767 tonnes because a great deal of the resource can be obtained from the recycling of spent fuel and former military ordnance.

Sweden does not appear above because exploiting its low-grade reserves is uneconomical at the present time. Eventually this situation could change because of scientific and technological improvements in mining and processing. Something that might cause a quantum jump in the value of Swedish uranium however would be the breeder reactor becoming a commercial proposition, because in that case the output of energy (due to the exploitation of the plutonium that could be bred) would be enormous for even low-grade uranium. As far as I am concerned, the Swedish government (and most other governments) are at present completely incapable of solving the security problems that would be posed by a greater presence of and/or reliance on plutonium. This may be the only point on which I happen to be in agreement with people like Ralph Nader and Amory Lovins. Unlike them, however, I happen to believe that by rejecting the energy in uranium when it is used in 'conventional' reactors, the (psychological) conditions are being created for a panic-stricken rush into the breeder when the fundamental scarcity of oil and gas is revealed to the television audience

An interesting factor here is that Sweden was – and may still be - surrounded by comparatively unsafe reactors: a total of six can be found at Sosnowy Bor outside St Petersburg (Russia), and Ignalina in Lithuania. In the film *The Deer Hunter*, Christopher Walken sang a drunken version of the marvelous tune 'I've got my eyes on you', and many nuclear experts in Sweden have had their eyes on Ignalina as an installation (of the Chernobyl type) that could pose a danger to this country, but not the 'Greens'. Their eyes instead have been fixed on safe reactors in Sweden, as well as the new super-safe facility that is now under construction in Finland, and which will have a rated output of 1600 megawatts, or as much as the two Swedish reactors that were closed at Barsebäck (near Malmö).

Somebody else with a keen interest in reactors is Mr Romano Prodi of the EU, who is one of the overseers of the ridiculous crusade to deregulate Europe's electricity and gas. Among the reactors in which he has taken a particular interest are those of Bulgaria, which the International Atomic Energy Agency (IAEA) considers to be on a par with the average in Western Europe. According to John Ritch, the US ambassador to the IAEA, the European

Commission has decided to “blackmail” Bulgaria in such a way as to make its entry into the EU contingent on its willingness to reduce its nuclear capacity.

Even a combination of John Maynard Keynes and Sigmund Freud would have a difficult time comprehending the reasoning here, although Mr Ritch feels that this scheme originates with the “antinuclear environmentalists” that play an important role in the Prodi team. This may be true, but as I pointed out in a talk in Milan several years ago, it may also have to do with a belief by the Prodi braintrust that since half of Bulgaria’s electricity came from nuclear reactors (as compared to 30% in Europe overall), electricity deregulation in that corner of Europe would be easier if Bulgaria’s nuclear capability was reduced. Theoretically this makes sense, because in Sweden competition – which was supposed to be the object of deregulation – *decreased* rather than increased after deregulation was introduced, and one reason is that large generators have been able to merge with smaller firms. On the other hand, it is possible to conclude that deregulation has achieved one of its goals, which is the illogical opening of the pseudo-market NordPool for the trading of electricity.

Nuclear and the Kyoto Hobby-Horse

As I have found out, it would not be a good idea in Sweden (and probably elsewhere) to belittle the Kyoto Protocol if you are planning to impress the Broad Masses with your wisdom – or at least that portion of them with the typically “deep interest” in environmental matters that characterizes the young know-nothings found at various research institutes in Sweden. The basic problem here is that this sub-set of the BM doesn’t really understand the issue. They don’t understand that at bottom the Kyoto Conference itself had little or nothing to do with reducing Greenhouse gases, and might best be described as an outstanding example of what George Orwell called *a system of indoor welfare*. Michael Hanlon, the science editor of the Daily Mail (UK) puts it as follows:

> “According to the environmentalist mullahs, there is only One Solution to global warming, and its name is Kyoto. The Japanese city in which a rather shambolic agreement to curb carbon dioxide emissions was signed some years ago has acquired talismanic status among people who one suspects have little idea what ‘Kyoto’ is, would do or how it works.” (2005).

Among the “people” that Mr Hanlon is describing were most of the ‘delegates’ to Kyoto, whose principal interest was to obtain tickets for the next climate warming jamboree. According to Professor Sven Kullander and several colleagues in the Swedish Academy of Science (2002), Kyoto was an important first step for reducing greenhouse gases, but “helt otillräckligt för en reell förbättring” (= completely insufficient for a real improvement). If readers can accept the latter portion of this judgement, then I accept the first part – although in reality I put the Kyoto meeting in the same category as the ‘World Summit’ in Capetown, where perhaps 60,000 heavy eaters and drinkers assembled to solve in their own gluttonous way the many and varied problems confronting contemporary societies.

Swedes accept Kyoto for the same reason that they accept electricity deregulation and the EU: they were told to accept it by celebrity politicians and journalists. The physicist Richard Feynman once said that in matters of the above nature the logic of science is superior to that of the authorities, but a hypothesis of that nature has no place in the pretentious deliberations and pronouncements of assorted media favourites, which assures that it is taboo for a large part of their audiences – at least when they are sober. Swedes are also great partisans of ‘emissions trading’, although an advisor to President Putin once called it a scheme to make money that is irrelevant for suppressing greenhouse gases.

Concluding Remarks

Let me sum up what I said in a recent article in the journal *Energy and Environment* (2004). We do *not* know if global warming is the real deal, or just part of a cycle; but we do know that gas and oil are running out, although it may take a few decades. In these circumstances the optimal behaviour is to get friendlier with the friendly atom, and do what Prime Minister Blair and the founder of Greenpeace suggest, which is to increase the use of nuclear energy. As suggested in this paper, that friendship will be necessary to supply the ‘extra energy’ needed to e.g. obtain the new fuels that voters in the energy importing countries have no intention of doing without, regardless of what they say. As Len Gould informed the forum EnergyPulse, these voters intend to have enough fuel to continue their transportation activities – much of which is mandatory if they are to maintain the standard of living of themselves and their families – even if they must go to war to obtain this commodity.

Germany is a country that, together with Sweden, has expressed an intention to abandon its nuclear ambitions. After the widespread distribution of my short paper ‘Some Friendly Economics for the Nuclear Energy Booster Club’, I received mails from several persons in that country and elsewhere requesting their names to be removed from the list of more than a thousand persons directly receiving my papers. I was especially surprised by one of these ‘Dear Johns’ that I received from Germany.

‘Wir Werden Wiedermal Marschieren’ (=We Will March Again) was the title of a book that gained considerable attention in Germany when I was in that country with the U.S. Army. It became a best seller, and was about the retaking by the German Army of places like the Sudetenland (in Czechoslovakia) in the coming Third World War, which the author of that book and his many readers saw as inevitable and necessary.

Early in my ‘tour’, the armies of Nato countries participated in perhaps the largest peacetime military exercise ever held in ‘West’ Germany, which was called ‘Apple Harvest’. Toward the conclusion of that exercise, the referees concluded that the Red Army had broken through the Fulda Gap and had almost reached Nuremberg, and the only way that they could be stopped was with nuclear weapons. I had the opportunity to review the calculations for one of the simulated nuclear projectiles fired from a large cannon at the advancing Red Army. Had it been real instead of simulated, the eastern suburbs of Nuremberg would have been decimated. After that outcome came to be known, German officers, journalists, book-club members, politicians and various decision makers lost their appetite for marching. The same kind of reversion will eventually happen when the German public comes to realize that abandoning nuclear energy could decimate their standard of living. Among other things it could mean that virtually every factory in Germany becomes a candidate for transfer to parts of the world with an adequate and reliable supply of energy.

This is the reason why I want the nuclear capacity in Sweden to increase! The issue is my pension. It is also the issue for many of my friends and neighbours, although they have been convinced by certain members of the anti-nuclear booster club and their favourite politicians that they would be doing themselves a disservice by understanding the easily understandable.

According to a gentleman who once expressed a desire for a public debate with me about global warming, letting nature take its course instead of trying to reduce CO_2 emissions is the correct thing to do, because even if we find ourselves in deep trouble, after a few hundred years of heavy ice and other discomforts, beautiful Stockholm might be more attractive. I must confess that I could not understand that kind of thinking, and so I graciously informed my potential debating opponent that clown time was over, because the only place that crank opinions of that nature could possibly be taken seriously is here in the Kingdom of Sweden, where things like electricity deregulation and EU membership make it clear to me that the First Law of Nature – self preservation – is slowly being repealed.

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