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Nuclear energy, an option for sustainable development ?

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1. Problem

This article attempts to answer the question of "does nuclear energy represent an option for sustainable development?" The latter implying the quest for human development[1] through a satisfactory combination of economic development and the natural environment's evolution. We thus broach the subject of nuclear energy through an interdisciplinary approach, under the angle of environment, health, economy, social acceptability, terrorism and nuclear weapon proliferation. More precisely, we examine the risks brought about by this form of energy. Our reflection on the perspectives of nuclear energy is based upon a retrospective analysis.

The article is organised as follow: we present the concept of risk in point 2. In point 3 we recall the paradigms of energy policy, which help to understand choices in past and current debates. Programs and achievements of the past are recalled in point 4, whereas realities of technical and economic performances are outlined in point 5. Point 6 reviews the problems that have caused failures of the past and that could prevent a new take-off. Foreseeable perspectives, from our point of view, are discussed in point 7. In the conclusion we answer our initial question.

2. Approach

We broach the subject of nuclear energy in terms of "risk"[2]. Risk designates the possible apparition of an event that may create negative consequences. However, one often exposes oneself in the hope of obtaining an advantage. In many cases, we may choose between several types of risk, which brings us to study relative risk. The risk must be identified and managed. Subjective attitudes towards risk must also be taken into consideration

Risk is defined by a hazard and the consequences provoked by its occurrence. The hazard represents the probability of occurrence of an event. It is characterised by its nature and in certain cases by its magnitude. Some hazards are independent of human will; others may be influenced by different types of measures. The hazard's occurrence can totally or partially affect the elements at risk. These elements comprise populations, buildings, infrastructures, economic activity, social relations, culture, public institutions and the environment. In order to evaluate the losses of elements at risk, we can take vulnerability into consideration. Vulnerability expresses the fact of being prone to or susceptible to damage or injury. We can

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* I thank the Federal Office for Education and Science for its support, as well as Clarice Ferraz, assistant, and Luke Gueriane, student, for their help.

[1] Sen A.K. (Cambridge University) (2000), *Development as freedom,* Alfred A. Knopf, New York.

[2] Romerio F. (CUEPE), *A concept of risk for the understanding of energy problems and their environmental and social implications* (forthcoming).

also introduce the concept of capacity, i.e. the fact of being prone to or susceptible to recovery. The interactions between vulnerability and capacity can engender phenomena of "destructive creation". The occurrence of some hazards can provoke a disaster. At the origin of the disaster, we may also have a strong vulnerability and a weak capacity. We are therefore confronted by major risks, which entail extraordinary losses.

Risk is a complex function of time and space. The hazard can appear almost instantaneously or gradually over time. It can have short, medium or long term consequences, on a local, regional or global scale. It can lead to instabilities and irreversibilities. The estimation of hazard, of vulnerability and of capacity can be surrounded by high levels of uncertainty. In order to understand these phenomena, natural, technological, economic and social systems must be studied, which can be highly complex.

Attitudes towards risk deeply influence decision-makers, experts and lay persons, as much in cases where we admit rational behaviour, as in the cases where we study actual behaviour. The latter is influenced by mental processes and intrinsic motivations, emotions, perceptions, memory, and other factors that have been named by psychologists by the term "framing" of a decision problem.

It is possible to reduce risk through the adoption of measures allowing the reduction of the probability of occurrence of the hazard, lessening vulnerability and reinforcing capacity. A lower vulnerability and stronger capacity allow a greater toleration of the presence of hazards.

On the one hand, the nuclear industry creates a risk of radioactive contamination, related to the occurrence of several hazards of natural, technical or military origins. On the other hand, the same hazards and others of political and economic origin provoke risk for the energy supply. Radioactive contamination represents a risk to health, resulting from the doses of radiation received by individuals. Certain categories of the population, for example children, are more vulnerable. The socio-economic effects of a contamination or of a supply disruption depend on the elements at risk, on their vulnerability and capacity, for example on the level of diversification of the energy supply (vulnerability), or on preparedness programs (capacity). Major risk is a reality of the nuclear industry. The problem of relative risk, notably the relation "nuclear energy – fossil fuel", can thus create a dilemma.

At present, a global evaluation of nuclear risk can only be undertaken through a qualitative approach. In fact, we are confronted by multiple phenomena that concern society, the economy, politics, health, the environment, technology, etc., which are extremely difficult to measure and bring to a common denominator. The uncertainties raise complex problems. Risk analysis must first be carried out adopting a qualitative approach. However, inevitably partial, more precise quantitative analyses are extremely useful for decision making.

It is possible to generalise the experiences of different countries concerning nuclear energy. National specificities may however provide results contradicting such generalisations on particular points.

3. Paradigms of energy policy

Since the 1950's, we have assisted in the definition of a paradigm in energy policy aiming to reduce the Western energy dependence through the development of nuclear energy[3]. This implied notably an increase of the share of electricity in the national energy balance. At the origin of this paradigm, there is the political situation of the 1950s and 1960s, deeply characterised by cold war and decolonisation. Furthermore, during this period, decision-

[3] Armand L., Etzel F., Giordani F. (Euratom and ECSC) (1957), Un objectif pour Euratom, *La Documentation Française, Notes et Etudes Documentaires,* 2291, p. 1-12.

makers manifested an extremely high level of confidence in technological progress. Governments and the economy hoped to create a new industrial sector through the development of nuclear energy. This paradigm was challenged by the antinuclear opposition and destabilised by the technical and economic problems encountered by the nuclear sector itself.[4]

The question of climate changes, particularly the Kyoto conference (1997), allowed the resurrection of the nuclear paradigm. The nuclear sector very quickly detected this opportunity[5]. However, we cannot subscribe to such a paradigm without taking into consideration the problems related to the risks brought about by this form of energy or without analysing past failures[6].

4. Programmes *versus* realisations

Table 1 shows the nuclear programs in the OECD countries of Western Europe since the 1950s. Horizontally, it shows the nuclear programmes set up between 1956 and 2001, for the years 1975 to 2020; vertically, it shows the change in these programs. They were very ambitious until 1982. The gap between programs and realisations is impressive. For instance, in 1978, planners believed to be able to increase nuclear capacity by up to 260 to 418 GWe by 1995; in fact, in 1995, the installed nuclear capacity was only 123 GWe.

Table 1 - Nuclear programmes and realisations in the OECD countries of Western Europe - 1956-2001 (GWe).

Programme defined in	Already set up	Programmes for the years							
		1975	1980	1985	1990	1995	2000	2010	2020
1956 a	< 1	33							
1960 b	< 1	10-35							
1966 c	6	40	90						
1970 d	10	34-42	79-118	142-263					
1973 d	16		73-85	155-204	280-448				
1975 d	19		65-79	165-212	262-380		409-804		
1978 e	26			107-146	195-273	260-418	310-560		
1979 d	41			100-113	165-209	224-291	275-407		
1982 e	47				142-158	171-219	223-317	329-557	421-803
1986 d	77				121	140	172		
1992 d	118					124	130	131	
1996 d	121						128	120-122	
2001 d	126							101 f	92-99 f
Realisations	19	47	92	120	121	123	126		

Sources: a OECE. *L'Europe face à ses besoins croissants en énergie.* b OECE. *L'énergie en Europe, Nouvelles perspectives.* c OCDE. *Politique énergétique.* d OECD. *Uranium, ressources, production and demand (red book).* e OECD. *Nuclear energy and its fuel cycle (yellow book).* f Without Germany.

[4] Romerio F. (CUEPE) (1998), The risks of the nuclear policies, *Energy Policy,* 26 (3), p. 239-246.

[5] Charmant A. et al. (CEA) (1991), La France sans nucléaire, *Revue de l'Energie,* p. 713-714. This article reaches the conclusion that "it is thanks to the nuclear program that today we are in a comfortable position: the levels of CO_2 emissions in France are amongst the lowest for industrialised countries" (p. 714).

[6] Dessus points out that "By focusing… on the greenhouse gas emissions' problem, we are likely to see the developing countries taking potentially dangerous routes for the sustainable development (nuclear power plants, large hydro plants, large sugar-can's surfaces for the alcohol production, etc.)" (Dessus B. (CNRS) (2003), Les défis énergétiques du développement, in Lachal B., Romerio F. éds., *L'énergie, controverses et perspectives,* Université de Genève, Collection Energie, Environnement, Société, p. 189).

5. Appearances *versus* realities

In the analyses carried out through the years, we find a great deal of wishful thinking; such analyses are not very transparent. Often, what is presented as a "reality" is nothing but a mere "objective to be attained". On the one hand there is the appearance, on the other the reality. In some cases, perhaps even the tools of analysis are chosen bearing in mind the desired results. For example, decision criteria in uncertain circumstances were not subject to a sufficiently attentive analysis. Yet Bessière had demonstrated that the application of the minimax criteria to a cost function leads "to count on the failure of nuclear energy"; the application of the same criteria to a regret function, leads to consider a partial success[7].

In the field of nuclear safety, there is no clear-cut distinction between "the objectives" and "reality", between "the safety sought for" and "the safety already implemented". In fact, the safety levels displayed simply do not come from the most reasonable estimations, rarely carried out and/or diffused. For instance, on the occasion of two conferences of the IAEA in 1988, the experts of the CEA pointed out that the probability of the core meltdown having unacceptable radiological effects was definitely higher than the levels sought after, i.e. 10^{-7} per reactor and per year. To face this problem, the French nuclear power stations were equipped with pressure relief systems and turbo-generators[8]. This contrasts with a usually much more reassuring attitude.

From an economic point of view, the production cost estimations represent an "objective to reach" most of the time. In England, the CEGB recognised that the variables used to estimate the production costs had "the nature of targets"[9]. The Select Committee on Energy of the House of Commons criticised the figures produced by the CEGB, because they were "difficult to follow, inadequately presented and based on questionable and often unspecified assumptions"[10]. At EdF, Ailleret pointed out that a "subconscious mechanism… leads us to choose the combination of parameters which fixes a competitive cost"[11].

It is worthwhile noting that we find the most interesting information and critical judgements on the conventional reactors in the papers that sought to demonstrate that the future belonged to breeder reactors.

6. Critical problems

Considering the differences between programs and realisations and between appearances and realities, we may wonder if the nuclear sector can do better and whether it deserves the population's confidence in the future. Here below we attempt to bring to light the risks that largely contributed in preventing nuclear development in the past and that may cause new short-circuits in years to come.

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[7] Bessière F. (EdF) (1971), Critère du regret minimax et décision dans l'incertain : application par EdF à l'avenir des équipements nucléaires, in Morlat G., Bessière F. éds., *Vingt-cinq ans d'économie électrique: investissements, coûts marginaux et tarifs*, Dunod, Paris, p. 210 (first published in 1961).

[8] Cornille Y. (CEA) (1988), Prévisions des accidents graves dans les REP en France, in *Proceedings of an International Symposium on severe accidents in nuclear power plants,* jointly organized by the IAEA and the NEA, held in Sorrento, v. 2, p. 608; Quéniart D. (CEA) (1988), L'utilisation de critères dans l'analyse de sûreté réglementaire en France, *Proceedings of an International Symposium on regulatory practices and safety standards for nuclear power plants,* jointly organized by the IAEA and the NEA, held in Münich, p. 358-359.

[9] The Monopolies and Mergers Commission (1981), *Central Electricity Generating Board: a report on the operation by the Board of its system for the generation and supply of electricity in bulk*, London, HMSO, 1981, p. 91.

[10] UK Selected Committee on energy (1981), *The Government's statement on the new nuclear power programme,* HMSO, London, p. 40.

[11] Ailleret P. (EdF) (1957), L'énergie nucléaire dans l'équipement énergétique français, *Revue Française de l'Energie,* p. 86-87.

a) Health effects of ionizing radiations

At low doses, ionizing radiations provoke a risk of cancer, leukaemia and genetic malformation[12]. The evaluation of these risks is tainted by relatively high margins of uncertainty. The controversies are all the more acute that the radioprotection is based on both scientific studies and on appreciations of an ethical, socio-economic, military nature, etc. It is difficult to say whether this will evolve in a favourable direction to the development of nuclear energy or not. For both society and nuclear industry this is an important source of uncertainty, which is destined to stay for a long time.

In order to illustrate the problem, we use the case of solid cancer risk. According to ICRP, the relationship between dose and effect (the risk) is linear. There is no threshold, below which there is no risk. The problem of the uncertainty is broached in the following terms: "The nominal values of fatal cancer risk... are not to be regarded as precise and immutable. They are unfortunately, at this time still subject to many specific uncertainties and to many assumptions involving factors which may be subject to change"[13]. This approach is challenged by two sets of studies which state that the risk is lower, respectively higher. According to the first set, the dose-effect model is linear-quadratic. The threshold may exist and very low doses may be beneficial to the individual's health[14]. On the contrary, according to the second set of studies, the dose-effect model is supra-linear. The threshold does not exist.

The problem of fixing dose limits is particularly delicate. The ICRP states that "It is mainly a value judgement which would need to be based, not only on the scientific information but also on knowledge of the level of risk that is usually considered unacceptable under normal conditions"[15]. It also points out that "the primary aim of radiological protection is to provide an appropriate standard of protection for man without unduly limiting the beneficial practices giving rise to radiation exposure"[16]. If we follow the first set of studies, we can relax dose limits and nuclear raises less worries; if however we follow the second set, we must limit the use of ionizing radiations to medicine.

b) Reactors safety

Major risk represents a Damocles sword hanging over nuclear energy's future. It is most present in the form of a potential core meltdown, which provokes the erosion of the reactor base, increase of the pressure inside the containment, hydrogen deflagration and containment failure. In which case there is release of radionuclides into the atmosphere and global, regional and local contamination. At Chernobyl we had to evacuate populations in a 30 km radius, create an exclusion zone and build a sarcophagus able to confine the reactors debris for hundreds of years. Vast regions of the Northern hemisphere were affected by radioactive clouds.

In a nuclear power station the main safety systems include: i. the negative reactivity coefficients, which provoke a reaction in the opposite sense if the neutron multiplication rate is to some degrees higher than 1; ii. the control rods, which permit to shut down the reactor in the case of an emergency; iii. the emergency core cooling system, which allows to remove heat from the reactor in the case of a loss of coolant accident; iv. the barriers (the fuel

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[12] Romerio F. (CUEPE) (2000), *Gérer le risque des radiations ionisantes,* Librairie Droz, Genève-Paris; Romerio F. (2002), Which paradigm for managing the risk of ionising radiation?*, Risk Analysis,* 22 (1), p. 59-66.

[13] ICRP (1991), 1990 Recommendations of the ICRP, ICRP Publication no. 60, *Annals of the ICRP,* 21(1-3), p. 136-137.

[14] We call this hypothetical phenomenon "hormesis".

[15] ICRP (1991), *op. cit.*, p. 189.

[16] ICRP (1991), *op. cit.*, p. 25.

cladding, the reactor pressure vessel, the steel and concrete containment), which reduce the risk of diffusion of fission products and actinides into the power station or outside, in case of a severe accident; v. redundancy of equipments, which reduces the risk of the loss of the nuclear power station vital functions.

The problem of estimating the probability of occurrence of a severe accident is particularly important. In fact, in which case it may not be possible to noticeably lessen vulnerability and raise capacity in order to reduce risk. One estimates such probabilities with the aid of event-trees. This means that we have to identify the events which can threaten the integrity of the safety system, the chain of consequences which they induce, the system's reactions, until the final result, which can be the return to normality or an accident. At the same time, we must associate a probability to each sequence. In this manner, we can assess the accident's probability.

Such estimations may however be biased by the following elements : i. Exhaustivity, which is an essential objective of this approach, but difficult to reach; ii. Data, which partially are provided by experience acquired in industries where the wear and tear problem poses itself diversely, notably due to the absence of ionizing radiation. iii. Common mode failures, which paralyse the redundant systems and "remain unworkable" for this approach (this expression has been used by the CEAs experts[17]); iv. Human behaviour, which is not always integrated appropriately to the architecture of event-trees.

There is notably the problem of robustness of these estimations, which causes doubt and opposition to nuclear energy. For instance, as pointed out by Apostolakis "For reactor safety systems, the validity of frequencies below the level of 3×10^{-4} per reactor year is suspicious because the occurrence of the unaccountable becomes an important consideration"[18].

Often, the risk of an accident is expressed by a mathematical expectation (the product of probability and consequence). This approach is not very satisfactory as the events considered bare an all or nothing nature. Furthermore, one must take into account the totality of the reactors existing in the region concerned by the study. If we note p the probability of an accident in a reactor, then the probability of observing at least 1 accident in a park of N reactors in the course of the year is $P_N = 1 - (1 - p)^N$. In cases where pN is low, we may simplify the expression as follows $P_N = p \times N$.

c) Radioactive wastes disposal

The nuclear sector must offer satisfactory solutions to the problem of radioactive waste in order to avoid making future generations suffer the consequences of our lifestyle. The highly radioactive repositories have to guarantee the containment of the fission products and the actinides for several centuries, even for several thousands of years. The MIT study on the future of nuclear energy stresses that "The management and disposal of high-level radioactive spent fuel from the nuclear fuel cycle is one of the most intractable problems facing the nuclear power industry throughout the world. No country has yet successfully implemented a system for disposing of this waste"[19].

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[17] In French "demeurent rebelles". Dupuis M.C. *et al* (CEA) (1980), Introduction progressive du concept de risque dans la réglementation technique de la normalisation française en matière de sécurité nucléaire, in *Proceedings of an International Conference on current nuclear power plant safety issues,* organized by the IAEA in Stockholm, 20-24 October 1980, v. 2, p. 474.

[18] Apostolakis G. (University of California) (1978), Probability and risk assessment: The subjectivistic viewpoint and some suggestions, *Nuclear Safety,* 19(3), 1978, p. 314-315.

[19] MIT (2003), *The future of nuclear power. An interdisciplinary MIT study,* MIT, p. 10.

The safety system for radioactive waste disposal is characterised by a set of barriers aiming to avoid migration of radionuclides towards the biosphere. It includes vitrified wastes (in the case of the reprocessing of the spent fuel), the canister, made of steel, copper or titanium, the buffer material (clay, bentonite, salt or other materials), and the host geological formation itself. However, the integrity of this system can be threatened by the following elements: i. The radionuclide migration to the biosphere: in this case, the safety is only guaranteed if the radionuclides are diluted into the surface water (which plays the role of a supplementary barrier[20]); ii. The geology, which poses the problem of a potential occurrence of rock fractures filled by water, as well as the possible impact of climate change; iii. Human intrusions, raising the question of social changes and institutional control in the very long term.

Because of the very long periods involved, most of the time it is not possible to validate the hypotheses on the waste repositories' behaviour through the classical experimental methods, as they are designed in natural sciences. Thus, scientists have to turn to the "archaeological and natural analogues", for instance to the analysis of ancient materials, the concrete of the Antiquity and the copper of the Renaissance, or to the study on the radionuclide migrations which have taken place in Oklo, Gabon, where a spontaneous chain reaction occurred two thousand million years ago[21]. This approach is interesting. However, we should not forget its limits, in particular the fact that it is very difficult to identify and understand under which conditions the phenomenon occurred.

d) Terrorism and proliferation

Following the 11th of September, numerous nuclear installations have been equipped with ground-to-air missiles in order to be prepared to face any possible attacks. Swiss Re pointed out that the attacks against the Twins and the Pentagon demonstrated that "this type of threat has become virtually immeasurable in terms of both severity and frequency of exposure"[22]. The concept of "Critical Infrastructure Protection" (CIP) has been analyzed by the U.S. National Academy of Science, which stresses the vulnerability of the electric power infrastructures[23].

The risk of proliferation is henceforth high, notably due to the presence of plutonium stocks of civil and military origin, of which part could be (or already has been) lost from national and international authorities' control. In 1999 it was estimated that the total quantity of plutonium already generated by nuclear stations in the world was around 1'000 tons[24]. Plutonium is at the origin of profound contrasts between the United Kingdom, France and Japan, which had opted for the reprocessing of spent fuel, and the United States that abandoned it in the 1970's. In CEA experts' opinion, by adopting the open cycle option, "we create… true plutonium mines"[25]. The Nuclear Energy Policy Study Group expresses another

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[20] Pigford T.H. (University of California) (1983), Long-term environmental impacts of geological repositories, in *Proceedings of an International Conference on radioactive waste management,* organised by the IAEA in Seattle, 16-20 May 1983, v. 4., p. 81-115.

[21] Mallison L.G., Davies I.L. (Taylor-Woodrow Construction Ltd) (1987), *A historical examination of concrete*, Commission of the European Communities, Luxembourg; *Proceedings of a Symposium on the Oklo phenomenon,* organised by the IAEA in co-operation with the French Atomic Energy Commission and the government of the Republic of Gabon, held in Libreville, 23-27 June 1975.

[22] Swiss Re (2002), Natural catastrophes and man-made disasters in 2001, *Sigma,* 1, p. 16.

[23] Farrell A.E., Zerriffi H., Dowlatabadi H. (University of California, Carnegie Mellon University, University of British Columbia) (2004), Energy infrastructure and security, *Ann. Rev. Environ. Resour.,* 29, p. 443.

[24] Chawla R. (Swiss Institute of Technology) (1999), L'énergie nucléaire dans un contexte global, in Lachal B., Romerio F. éds., *Quels systèmes énergétiques pour le XXI^e^ siècle ? Production,* Université de Genève, Collection Energie, Environnement, Société, p. 327.

[25] Ferrari A. *et al.* (CEA) (1977), L'utilisation du plutonium, in *Proceedings of an International Conference on nuclear power and its fuel cycle,* organised by the IAEA in Salzburg, 2-13 May 1977, vol. 3, p. 252.

point of view: "short-term risks of reprocessing and recycling outweigh the relatively small reduction in long-term risks"[26].

The risk of proliferation is also related to the dirty bomb, in which radioactive material (from any source, such as nuclear spent fuel or cobalt used in medicine) is dispersed using conventional explosives.

e) Returns

It is difficult for nuclear power generation to be profitable. In fact, the opening of electricity markets to competition penalises investment projects that are capital intensive, have long pay back periods, have little flexibility and entail relatively high risks. The costs of nuclear can be mastered as well in a monopolistic regime as in a competitive one. In some cases, the CEGB for example[27], public monopolies managed nuclear investments very poorly; the search for efficiency induced by competition may even improve its performance. However, in a competitive environment the nuclear industry is much more exposed to risk. In this respect, one must make the distinction between the intrinsic risks of nuclear technology (for example that of a severe accident), the economic risks (price volatility, etc) and the political and regulatory risks (antinuclear opposition, etc).

Discount rates reflect risk and have an important influence on the determination of cost prices per kWh, due to the high intensity in capital. Fuller and Hinman show that the discount rates used by financial markets on nuclear power shares IOUs is due to the greater perceived risk of nuclear power and not necessarily to lower profitability[28]. They point out that in the United States "a 3% increase in the allowed rate of return for nuclear utilities (from 13.7% to 16.7% in 1988) would have been necessary to fully offset the discount associated to nuclear power"[29].

The low level of flexibility of nuclear technology represents another inconvenience. As stated by Dixit and Pindyck, "When a firm makes irreversible investment expenditure, it kills its option to invest… This lost option value is an opportunity cost that must be included as part of the cost of the investment"[30]. The life expectancy of nuclear power plants represents a considerable source of uncertainty. The topic is highly controversial; estimations vary between 30 and 50 years. The new EPR fixes a life expectancy of 60 years[31].

The cost of plant decommissioning should represent up to 25% of the initial investment costs, according to the nuclear sector[32]. Waste disposal costs should be more favourable, of "a few percent of the price per kWh"[33]. However, we share Macdonald and Page's judgement, who

[26] Nuclear Energy Policy Study Group (Sponsored by the Ford Foundation) (1977), *Nuclear power, issues and choices,* Ballinger Publishing Company, Cambridge MA, p. 329.

[27] A judgment of Rand Corporation: "the persistent British pursuit of alternatives to the LWR can be best characterized as a function of scientific taste and national preference, without much regard for the contemporary realities of either technology or economics" (Perry R. *et al.*, *Development and commercialization of the light water reactor, 1946-1976*, Rand Corporation, Report R-2180-NSF, Santa Monica CA, 1977, p. 73).

[28] Fuller R.J., Hinman G.W. (Washington State University) (1990), The impact of nuclear power on the systematic risk and market value of electric utility common stock, *The Energy Journal,* 11(2), p. 131.

[29] Idem, p. 117.

[30] Dixit A.K., Pindyck R.S. (Princeton University and MIT) (1994), *Investment under uncertainty,* Princeton University Press, Princeton, p. 6.

[31] Secrétariat de la Mission (2000), Prospective economic study of the nuclear electric network (summary of the report commissioned by the Prime Minister), *Revue de l'Energie,* 519, p. 395.

[32] NEA (2003), *Decommissioning nuclear power plants. Policies, strategies and costs,* Paris, p. 10. We suppose a water reactor and an initial investment of US$ 2'000/kWe.

[33] OCDE (1993), *Les coûts de l'évacuation des déchets hautement radioactifs dans des formations géologiques,* Paris, p. 82.

point out that "given the nuclear history of unfulfilled expectations, more is required than a simple expression of confidence in one's own estimates"[34]. One also encounters the problem of good management of special funds created in order to assure the covering of decommissioning costs as well as those of waste disposal.

Fuel on the other hand represents a comparative advantage in nuclear favour. In fact, the price of uranium has little impact on the cost price of electricity. Uranium resources are relatively abundant and are well dispersed geographically. The problem of their depletion was only ever an issue when considering very ambitious world-wide nuclear programmes, entailing the construction of off-shore nuclear plants, 3'000 nuclear parks according to Weinberg and Hammond, "some of these... preferably, floating offshore on huge barges"[35].

The nearest contender to nuclear power is most likely to be combined-cycle gas turbines (CCGTs), for which thermodynamic efficiency is close to 55-60%[36]. In fact, their pay-back time, including the time required to plan and build a new plant, is relatively short. One can carry out small sized investments (100 MW). They have the advantage of a good flexibility. Furthermore, "The cost figures for CCGTs are well-established in the market place, while those for nuclear power are infamously uncertain"[37]. The disadvantage of CCGTs lies in the evolutions in gas prices and in taxes on CO_2. Long term take-or-pay contracts can only partially hedge these risks. One should not however anticipate nuclear competitiveness based purely on gas price rises. In the past, similar estimations were made based on coal prices and later lead to unpleasant surprises for the nuclear sector.

f) Nuclear energy market share

The extremely ambitious nuclear programs of the past, that included notably the development of breeder reactors, up until the economic disaster of Superphenix in France[38], are no longer conceivable today. On the contrary, we should promote diversification, as we suggest further ahead.

Nonetheless, there is always the risk of attempts to promote electricity consumption, against efficiency programmes, in order to facilitate nuclear power's penetration into the market. This strategy is inconsistent with sustainability. It was developed in several counties in the 1970s. EdF for example, suggested intensive commercial actions to promote the thermal applications of electricity. It was that "The opening of markets constitutes a key point to the creation of an *all electrical* reflex in matters of comfort"[39].[40]

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[34] Macdonald N., Page B. (Ernst and Young) (1991), Achieving credibility in decommissioning estimates, in *Proceedings of an International Seminar on decommissioning policies for nuclear facilities,* organised by the NEA in Paris, October 1991, p. 193.

[35] Weinberg A.M., Hammond R.P. (ORNL) (1971), Global effects of increased use of energy, *Proceedings of the U.N. International Conference on the Peaceful Uses of Atomic Energy,* Geneva, vol. 1, p. 176.

[36] Pfeifenberger J.P., Hanser P.Q., Ammann P.R. (The Brattle Group) (1997), What's in the cards for distributed resources ?, *The Energy Journal,* Special Issue on Distributed Resources, p. 1-2.

[37] MacKerron G. (NERA) (2004), Nuclear power and the characteristics of ordinariness – the case of UK energy policy, *Energy Policy,* 32, p. 1960.

[38] Finon D. (Université de Grenoble) (1989), *L'échec des surgénérateurs, Autopsie d'un grand programme*, Presses Universitaires de Grenoble. Faced by such technological failures, Boiteux, honorary president of EdF, suggests "putting the key under the door, gathering the modest knowledge already acquired at a high price" (Boiteux M. (1993), *Haute tension,* Editions Odile Jacob, Paris, p. 208). From this point of view, it is useful to note that the pilot fast breeder of 500 MW that was under construction on the Kalpakkam site, 80 Km south of Chenai (India), comprising installations for the extraction of plutonium, was damaged by the tsunami that devastated Asia on the 26th of December 2004 (cf. *The Indian Express,* 29.12.2004).

[39] Dubois J. (EdF) (1971), Position d'Electricité de France et du Gaz de France sur le marché de l'énergie, *Revue Française de l'Energie,* Mars-avril, p. 221.

g) Nuclear energy's social acceptability

Population's opposition can prevent nuclear energy's development. The problems previously mentioned partially explain these oppositions. Attitudes towards risk and more generally the subjective dimension of risk play an even greater role.

Prospect theory[41] shows that the displeasure associated with a loss is greater than the pleasure associated with a gain of a comparable dimension. Individuals are not concerned with final values of wealth *per se*, but with changes in wealth relative to some reference point. These changes become less and less important as losses and gains increase. Individuals tend to overestimate very low probabilities and underestimate intermediate and high probabilities.

This theory can help understand the opposition to nuclear energy. In all likelihood, one overestimates the probability of occurrence of a disaster that is in fact very low for a single reactor. Gains and losses (in both absolute and relative terms) are evaluated in an asymmetric manner. Even more so that the perception of radioactivity as a causal factor of cancer, leukaemia or of malformations drive individuals to consider their high vulnerability and that of their offspring. Their health prevails, it is unique.

It is difficult to say whether nuclear opposition will grow or weaken in the future. Willy-nilly, the expression of popular will must be respected in democratic countries. Moreover, as stated by Slovic, "Each side [expert and public] must respect the insights and intelligence of the other"[42].[43]

7. Perspectives

The risks provoked by nuclear energy are considerable. Major risks are inevitable. As stated by the MIT, "We have not found and, based on current knowledge, do not believe it is realistic to expect that there are new reactor and fuel cycle technologies that simultaneously overcome the problems of cost, safety, waste, and proliferation"[44]. Public concern on this subject cannot be dismissed as "radiophobia"[45].

Fossil fuels also provoke major risks, related to emissions of CO_2, SO_2, NO_x and particulates. Certain meteorological phenomena stir up public concern. However, the carbon-free character of nuclear power does not appear to motivate the general public to prefer expansion of the nuclear option. There is also the problem of depletion of natural resources. Coal reserves that are in the order of 200 years could be exploited through the development of underground

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40 Another counterproductive strategy is that mentioned by the MIT provoking a negative reflex towards renewable energies: "Most of the change [of the perceptions about nuclear energy] would come through education about the high price of alternative energy sources, such as solar and wind" (MIT (2003), *op. cit.,* p. 72).

41 Kahneman D., Tversky A. (University of British Columbia and University of Stanford) (1979), Prospect theory: An analysis of decision under risk, *Econometrica,* 47, p. 263-291.

42 Slovic P. (University of Oregon) (1987), Perception of risk, *Science,* Vol. 236, April 27th, p. 285.

43 On this subject, it is useful to recall the Swiss industrial, Walter Boveri's (Brown, Boveri & Cie) point of view: "technical progress certainly does require cooperation, but it is essentially antidemocratic"; "if we really do want progress, it is not possible to consult third and fourth parties" (Boveri W. (1956), Problèmes actuels de l'énergie nucléaire en Suisse, *Revue Commerciale et Financière Suisse,* Avril).

44 MIT (2003), *op. cit.,* p. 76. In spite of the improvements in the reactors' design, new advanced design, combination of passive and active features in order to enhance reliability, advances in waste disposals' geologic and engineering system design, creation of small reactors, cost reduction, etc., that we should acknowledge.

45 IAEA expresses the same point of view: "The nature of these [psychological] effects is complicated and is wrong to dismiss them as irrational or to label them as radiophobia" (IAEA, *The International Chernobyl project, Summary brochure,* Vienna, 1991, p. 9).

gasification[46]. There remains the problem of CO_2 sequestration and its disposal, which is no less complex than that of nuclear wastes.

Energy efficiency holds the great advantage of avoiding the need to transform further energy. However, it is not free and its potential is not sufficient, notably in consideration of the emergence of the big Southern countries. Unless of course, we were to undergo drastic changes in our lifestyles. New renewable sources can't provide enough energy at reasonable price in the near future.

The nuclear option is therefore acceptable. We would like to recommend its abandon, but we know that it is not possible. We must however envisage diverse and flexible strategies. By flexibility, we mean the possibility to adapt choices in accordance with evolutions in uncertainties. By diversification, we mean the creation of well balanced portfolios, containing different energy resources, as little correlated as possible, with the exception of certain particular cases, such as when for example returns on energy investments are negatively correlated with returns on other investments, they represent insurance policies for the future[47]. The approach of diversification and flexibility would have the advantage of facilitating the search for a compromise between different energy policy conceptions.

The degree of diversification must be able to vary with time in function of policy evolutions and energy market evolutions, as well as with relative risks and their perception. It is not possible to study this problem in this article. The scenario proposed by the MIT study is interesting, but cannot be applied as it is without carrying out detailed discussions. We limit ourselves to providing some enlightening data. This study considers the deployment of 1'000 reactors of 1'000 MW each worldwide by 2050, which represents about 19% of the electricity generation (they suppose an electricity production growth rate of 2%). In 2000, nuclear energy represented 17% of world electricity production. With 1'000 reactors in 2050, it is possible to displace 5-15% of the yearly anthropogenic carbon emissions in 2050. With 1'000 reactors and a probability of a serious reactor core accident of 10^{-5} per reactor year ("a desirable and possible goal" with advanced LWR according to the MIT), the number of accidents expected during the period 2005-2055 would be less than 1.[48]

If the nuclear option is developed, we shall refuse wishful thinking, the lack of transparency and evaluations carried out by experts of questionable independence. In the past, we often made commonplace of the problems and erased uncertainties in the aim of creating consensus on very ambitious nuclear programs. In reality, this approach discredited work carried out by very dedicated professionals, often of a very high standard. Moreover, we lost confidence in national and international commissions of experts, since they consisted almost exclusively in representatives from the nuclear sector. Confidence in nuclear energy cannot be established without guaranties of transparency and the implication of independent experts, open to different movements of opinions expressed by academic and civil societies. As stated by Hermitte, "Expertise must be organised in such a manner that controversies and contradictions are manifest and that officials can make decisions with their consideration"[49].

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[46] Coëme A., Fievez P. (IDGS) (1999), La gazéification souterraine dans le contexte énergétique de l'an 2000, in Lachal B., Romerio F. éds., *op. cit.,* p. 229-239.

[47] Lind R.C. (Cornell University) (1982), A primer of the major issues relating to the discount rate for evaluating national energy options, in Lind R.C. ed., *Discounting for time and risk in energy policy*, Washington-Baltimore, The Johns Hopkins University Press, 1982, p. 63.

[48] MIT (2003), *op. cit.,* p. 26 and 48.

[49] Hermitte M.-A. (EHESS) (1998), Pour une Agence de l'expertise scientifique, *La Recherche,* Mai, p. 95-97. On these issues, cf. Lachal B., Romerio F. éds. (CUEPE) (2003), *op. cit*.

8. Conclusion

Nuclear energy might represent an option for sustainable development as long as it is used with a great deal of precaution. Its interest must be judged with regards to diversified and flexible portfolios containing notably energy efficiency programs. If necessary the market should be oriented towards the desired direction using appropriate means[50]. The subjective attitude towards risk should be respected; it represents a key factor of the problem. The risks run, especially major risks, should not be lost of sight; they are spread over hundreds of years and touch the environment, health, economics and society. In this respect, we must require the greatest transparency and the implication of independent experts.

Abbreviations

CCGTs	Combined-Cycle Gas Turbines
CEA	Commissariat à l'énergie atomique (France)
CEGB	Central Electricity Generating Board (United Kingdom) (dissolved in 1990)
CNRS	Centre National de la Recherche Scientifique (France)
CUEPE	Centre Universitaire d'Etude des Problèmes de l'Energie (Université de Genève)
EBRD	European Bank for Reconstruction and Development
ECSC	European Coal and Steel Community
EdF	Electricité de France
EHESS	Ecoles des Hautes Etudes en Sciences Sociales (Paris)
EPR	European Pressurized Water Reactor
Euratom	European Atomic Energy Community
IAEA	International Atomic Energy Agency
ICRP	International Commission on Radiological Protection
IDGS	Institution pour le Développement de la Gazéification Souterraine (Liège)
IOUs	Investor Owned electric Utilities
LWR	Light Water Reactor
MIT	Massachusetts Institute of Technology
NEA	Nuclear Energy Agency
OCDE	Organisation de Coopération et Développement Economiques
OECE	Organisation for Economic Co-operation and Development
ORNL	Oak Ridge National Laboratory

[50] Romerio F., Ferraz C. (CUEPE) (2005), *Security of supply and renewable energy in the light of the opening of electricity markets to competition,* Investing for Sustainability, 5th SESSA Conference, Universidad Pontificia Comillas, Madrid, May 19-20.