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MULTICRITERIA ANALYSIS OF THE IMPACTS
OF ENERGY ALTERNATIVES :

A SURVEY AND A NEW COMPARATIVE APPROACH (*)

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ANALYSE MULTICRITERE DES IMPACTS
DE CHOIX ENERGETIQUES :
TOUR D'HORIZON ET NOUVELLE APPROCHE COMPARATIVE

RESUME

Ce cahier traite du problème de la comparaison des choix énergétiques du point de vue de leurs impacts sur la santé humaine et la société. Les conditions à remplir pour réaliser une comparaison rigoureuse sont d'abord exposées. On décrit ensuite le modèle multicritère utilisé pour comparer, dans le contexte français, six filières électrogènes : pétrole, charbon, nucléaire (PWR), solaire thermique type "Themis" et type "thek", et solaire photovoltaïque.

La méthode utilisée est du type Electre, basée sur l'analyse de la concordance et de la discordance des critères. Elle permet également de rendre compte des incertitudes, étant donné que la modélisation des préférences est effectuée par des relations de surclassement floues. Nous avons développé ensuite quatre stratégies énergétiques portant sur des hypothèses réalistes qui nous ont permis de bien tenir compte des positions des divers groupes sociaux impliqués dans ces choix. Les résultats auxquels nous sommes parvenus correspondaient assez bien à ce qu'on sait des prises de position de ces groupes. Cela rend la méthode un outil performant, non pas seulement pour légitimer des choix collectifs mais également et surtout pour l'aide à la décision dans ce domaine.

MOTS-CLE : Filières énergétiques, analyse multicritère, relation de surclassement floue.

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ABSTRACT

This paper deals with the problem of comparison of energy alternatives from the social and public health point of view. First the conditions required for an accurate comparison are outlined. Then a large multicriteria model is carried out in order to provide the framework for comparison of six energy chains : oil, coal, nuclear, solar thermal Themis, solar thermal Thek and Solar photovoltaic specified in the French conditions.

The method used is the ELECTRE type and is therefore based on an analysis of the concordance and discordance of criteria. It also allows us to take into account uncertainty, since modelling of preferences is done by fuzzy outranking relations. We then developed four energy strategies based on realistic hypotheses, which allowed us to take into consideration the points of view of the various social group involved by this problem of energy choices. The results that we arrived at coincide with what are known to be the stands of these groups. This make the method a particularly useful tool, not only to help justify a choice, but above all as a decision-aid.

KEY-WORDS : Energy technologies, multicriteria analysis, fuzzy outranking relation.

I. INTRODUCTION

The emergence of energy as a public issue is generally attributed to anti-nuclear protests, but in fact energy choices have been collective and have involved political decisions for a long time now. Since World War II, energy developments in France have rarely been dictated solely by the law of the marketplace. Once peace was established, the French found themselves engaged in the "battle for coal" and when this was won, there was a national drive to develop hydraulic power. Attention was concomitantly paid to reconstructing a national oil industry and to creating a nuclear industry.

The central role of energy in the French economy and the strategic need for national control was sufficient to justify and orient strong State intervention. In the aftermath of the war, there were so many shortages -the last was set off by the Suez crisis- and so few alternatives, that it is easy to understand why these major projects met with no resistance and, indeed, were widely supported. In the Fifties, the need to compare the advantages of various types of energy production led Electricité de France (EDF, the national electricity board) to undertake a number of studies summed up in the so called "note bleue". The government also set up the PEON commission ("production of electricity of nuclear origin"), which to this day continues the technical and economic data necessary for comparisons between the various types of nuclear systems and between the latter and conventional systems. (cf /47/).

Starting in the Sixties, it was in the United States that a series of comparative studies was undertaken, which were destined not only for decision-makers but for the public as well. They concentrated on environmental impact and public health effects of energy installations. Because of public pressure, the question of risk, which is in itself quite complex, was added on to those of economic profitability and of needs to be met. The earliest studies (cf /25/ and /68/) were relatively straightforward but they became increasingly complex as more and more criteria were introduced into evaluations (see, for instance, (/7/, /44/)) and as renewable sources of energy were taken into consideration (see /39/, /28/). The

situation has become so complex that there are now studies to "compare" comparisons (cf /54/, /10/, /21/). Indeed, results vary significantly, for the bases of comparison and the methods used to handle diverse criteria simultaneously are rarely the same and even the figures chosen vary. This explain why there is a large margin of uncertainty on, for example, the projected price of oil, the health effect of atmospheric pollution, the probability of a major accident in a power station or the stock of uranium resources.

Since the outbreak of the economic crisis, yet another criteria has been added, that is, the creation of new jobs depending upon the type of energy developed. Today all these criteria enter into the energy debate, so much so that there is a tendency for them to overlap : studies on health effects also often include economic effects and vice versa. Ecologists attack breeder reactors on economic grounds and advocates of nuclear energy attack the coal industry on environmental grounds. Given this, decision-makers are asking for many more comparative studies. In May 1979, for example, the ministers of the environment of the OECD countries launched the COMPASS program ("Comparative Assessment of Environmental Implications of various energy systems"). In France, the recent parliamentary debate on energy was based on two reports, one presented by the government (/9/), the other by the Chamber of Deputies (/3/). What they had in common was that they both presented in a neutral way a series of criteria on which to base evaluations. The role of elected representatives was even defined as follows : "The choice of energy solutions is an eminently political decision for it consists of determining the respective importance of criteria that must be taken into consideration" (see /3/, p.41).

A somewhat similar approach has been used in this study, which is a multi-criteria analysis of energy choices. Moreover, an appropriate methodology allows us to take into account the various uncertainties surrounding the evaluation of effects related to different energy policies. The method is applied to a less comprehensive problem than a global energy policy : that is, to define the technique designed to meet most of the electricity needs of the country by about the year 2000. This is not as restrictive as it might appear at first glance, for although electricity accounts for barely one-third of total energy consumption, it is

nonetheless the principal variable upon which a national body can act. Other energy sources correspond either to specific uses or else to too diffuse uses for efficacious collective action to be taken.

Six techniques will be examined : nuclear-PWR, oil, coal, solar photovoltaic, as well as two forms of solar thermal energy : a station with a tower like the Themis plant and a station with independent heat collectors like the Thek plant. In the following section, we shall present the formulation of the comparative analysis. The methodology of the multi-criteria approach used will be examined in section 3, while its application and the results obtained will be found in the last section.

2. FORMULATION OF THE COMPARATIVE ANALYSIS

2.1. Summary of comparative studies

Studies that compare social costs, health impacts and external effects of different sources of energy have been undertaken in France since 1978 (see /21/, /18/). In this brief review, we shall point out the effects that were considered, the energies that were examined and the goals of these analyses.

For the most part, comparative studies concentrated on systems for electricity production, with the exception of a few recent studies (cf. /28/, /7/). While early analyses were limited to the study of the effects of a power station, (cf /55/, /11/), they now encompass entire energy chains, i.e. all the technical processes needed to transform a raw material into usable energy. Most often, the negative effects of a technology are presented but in some cases an attempt has been made to define the optimal policy for electricity production (cf. /15/, /8/, /62/, /50/, /6/). In the latter case, the local and national points of view may be at odds. The aim of these studies was to see if nuclear energy presented greater risks than other forms of energy, but also to define acceptable levels of protection by comparing them to other industries. For instance the norms for workers in the nuclear industry were justified by comparing them with the rest of industrial activities (cf. /38/, /37/). These levels were also defined by cost-benefit optimization of greater protection and safety measures. In fact, risks are rarely presented as criteria on which to base

choices, and most studies only try to prove that they are "acceptable". Recently, reports have been prepared with a view to a political decision, and all the criteria are presented on the same plane to decision-makers : these are the COMPASS project and the HUGON and QUILES reports (cf. /9/, /3/).

Table I lists the types of criteria chosen for these comparisons. It is worth drawing attention to the variety of themes considered, which corresponds to the multiple approaches possible to energy questions : producing a balanced energy sheet ; ensuring national independence ; producing energy economically ; and adapting to the industrial and economic system. It also reflects the nature of the obstacles to be overcome, health effects, risks of catastrophes and of shortages, climatic effects, and so on. Even so, a number of criteria have not been considered : for example, domestic risks or deadlines for getting a given technology into operation. Such effects as employment have only recently been considered, and it is difficult to ascertain that all parameters of the energy problem have in fact been examined. Indeed, energy systems play so great a role in the economic and social life of a nation that no sooner does a new problem crop up than the energy repercussions become evident. In France, for example, where there is a move to decentralize power and decision-making, the distinction is now being made between centralized and decentralized forms of energy.

If it is possible to present a typology of these studies, it is unfortunately impossible to use their results as given. First, all the criteria are not necessarily quantifiable. In regard to quantification, we wish to stress that it introduces a bias, and that quantified data too often have more influence than qualitative. The heating up of the earth's atmosphere for instance, may often count less in people's opinion than, say, the number of workdays lost because of illness. Secondly, figures may often be imprecise, either because of scientific, statistical or accounting uncertainties. Above all, the principles of comparison vary from one study to the next : they can be limited to a power station or can be applied to an entire cycle ; sometimes the impacts of the energy produced are normalized and sometimes they are not ; the effects of the construction of an installation are at times taken into account and at other times are not. Lastly, specific conditions pertaining in a country for example, the origin of raw materials, the social security system,

population density or the more or less rigorous safety regulations all have an effect on costs, risks, their measurement, and so forth.

Therefore, before we attempt to analyze the criteria, we feel it is necessary to present the method and principles that guided the comparative approach used here and which is described in detail in /32/, /33/, /34/.

TABLE I : Criteria envisaged

CRITERIA	STUDIES
. Consumption of natural resources (raw materials, water land)	3/4/6/7/9/13/15/25/27/39/ 44/50/56/62/67/68/71/
. Damages to natural environment	4/7/8/13/25/27/30/31/35/40/44/50/56/ /62/64/67/68/71/
. Health effects Normal operation	/1/3/4/7/8/9/11/13/15/22/25/26/27/ 30/31/35/39/40/42/44/46/48/49/50/55/ 56/60/62/63/64/67/68/
Accidental situations	4/7/8/11/13/15/25/35/39/40/44/46/49/ 50/55/56/60/63/
. Long-term effects (CO ₂ , waste)	3/4/7/8/31/44/50/56/60/
. Effects on local economy	3/7/56/
. Macro-economic effects	3/6/7/9/31/42/50/67/68/
. National independence	3/6/7/9/15/44/60/
. Direct cost	3/4/6/9/15/26/31/44/46/60/62/67/68/71/
. Effect on employment	3/9/42/
. Energy balance-sheet	3/7/8/9/13/15/26/42/44/50/60/

2.2. Alternative scenarios

A comparative analysis must never neglect the two principles of exhaustivity and normalization. That is to say, the energy chains must be considered in their entirety, and impacts must be compared to the same electricity production. To obtain an exact definition of a chain, one must know the quality of the ore, the origin of supplies, the technologies being used, and so forth. This set of hypotheses

can be rendered coherent only within the framework of a supply scenario. At the end of the analysis, the factor one is supposed to use for normalization -the quantity of electricity produced- also poses a problem. Electricity is not a "place" in the economic sense of the term and, in particular, it cannot be stored. It is impossible to add a Kwh produced during off-peak hours and a peak-hour Kwh ; they have neither the same value nor the same production cost. To establish a valid comparison, one must be sure that the techniques under consideration furnish the same quantity of electricity at the same point of the demand curve. The simplest way to do this is to use supply-and-demand electricity scenarios.

These two principles have led to the use of alternative scenarios. Looking at the demand for electricity in 1990 in France, a fraction -the bulk of electricity consumption- is defined and, for each technique, an alternative scenario is worked out to meet that goal. This method provides a solid logical framework. Thanks to this framework, it was for example possible to determine how construction of equipment could be taken into account. If the 1990 reference appears to be restrictive, it is nonetheless possible to extrapolate for other future dates. As a matter of fact, the absence of such a reference to the economic and social situation in France in a given year, would not permit a better extrapolation. The only difference is that the hypotheses are explicit in the present study and not implicit.

This approach proved successful in dealing with three conventional chains ; PWR, oil and coal. However, it was difficult to do the same with solar options. In the first place, the year 1990 is too close to hand to consider that these technologies will be developed on an industrial scale. Moreover, it is possible that the demand curve for electricity will be modified should solar energy be used (see /24/). We therefore limited ourselves to normalizing impacts by the quantity of electricity. We concentrated primarily on extrapolating the characteristics of an industrial-type installation based on such existing prototypes as the Themis plant or the Thek collectors. Similarly, we were obliged to postulate the development of photovoltaic chains.

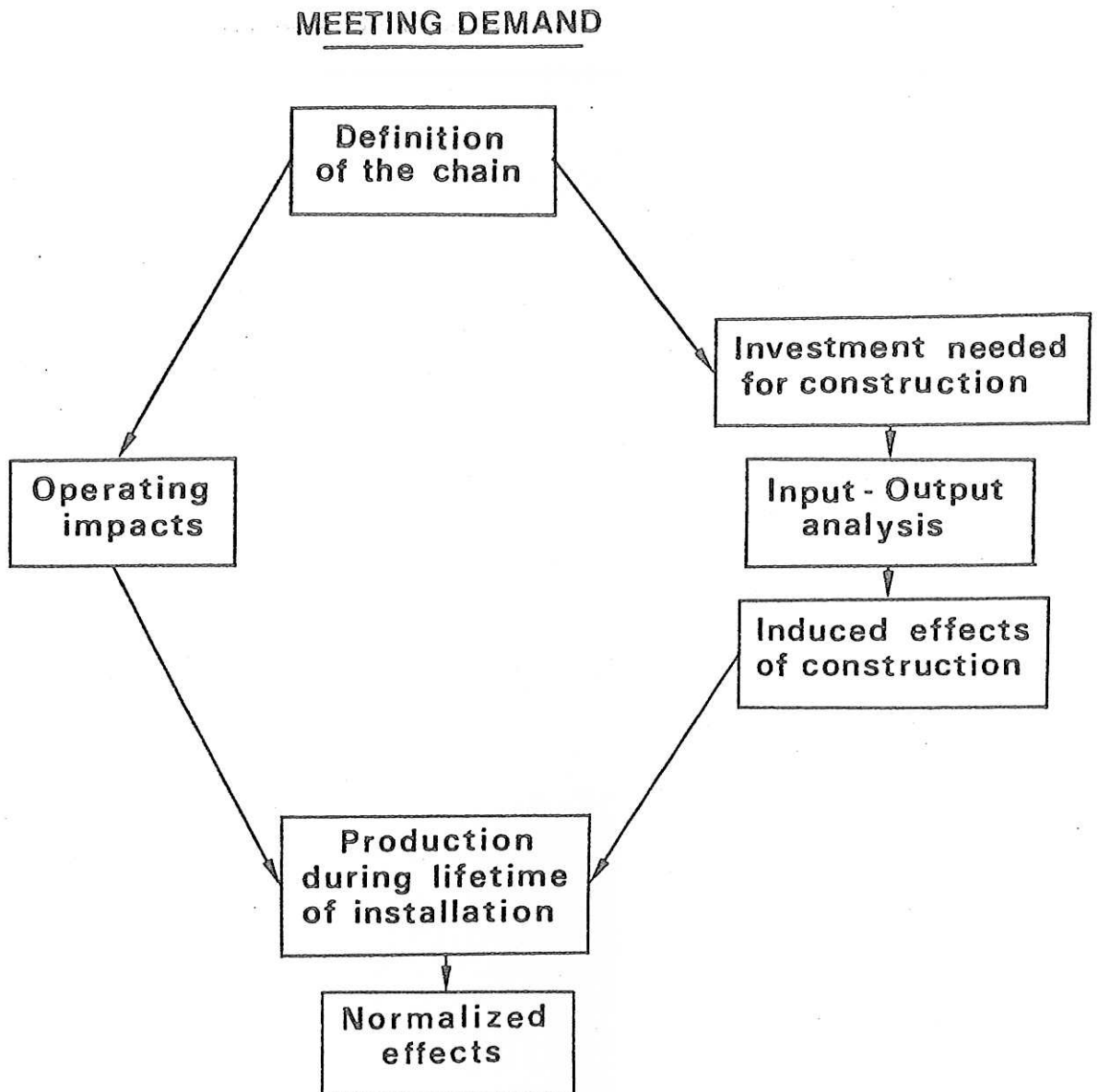


Figure 1 : Flow-chart of the evaluation of effects.

Once the scenarios and techniques are determined, the subsequent steps can be summarized as shown in Figure 1. Inquiries on the operation of a chain allow one to evaluate the various effects it will have. For example, one can evaluate the health effect on workers, the releases of radioactive waste, and the like. As is done for the number of workers needed, these can be calculated by simple statistics or one can use a series of complex theoretical models (see /5/ for example). Radiological impact thus brings into play models for atmospheric transfers and flows in the food chain, as well as relations between radiation doses and cancerogenic effects.

Concurrently the impact of construction is evaluated, this time using a macroeconomic analysis. Starting with the investments necessary for the construction, and having taken the dynamic effects on the economy into account thanks to an input-output analysis, coefficients related to branches of the economy are used to determine their impacts. To obtain the number of jobs to be created, one must use productivity figures (see /41/) or to measure risk for workers, one takes the risk coefficient of the french social security system (see /14/).

Generally speaking, the impacts on public health and on the economy of an energy technique are attributed in part to the construction phase and in part to the operating phase : the total production of a given installation and its expected lifetime are thus the parameters needed to calculate the total normalized impact of the produced energy.

2.3. The choice of criteria

Figure 2 shows the way in which the set of criteria used in this analysis was devised. It should be remembered that the decision is supposed to be based on a choice of the main electricity-producing chain to be used in France on a middle or long term basis. As a first step one can establish three distinct fields that will be affected.

The first is concerned with the energy needs to be met, which is of course the aim of any development of an energy chain. Three criteria were chosen

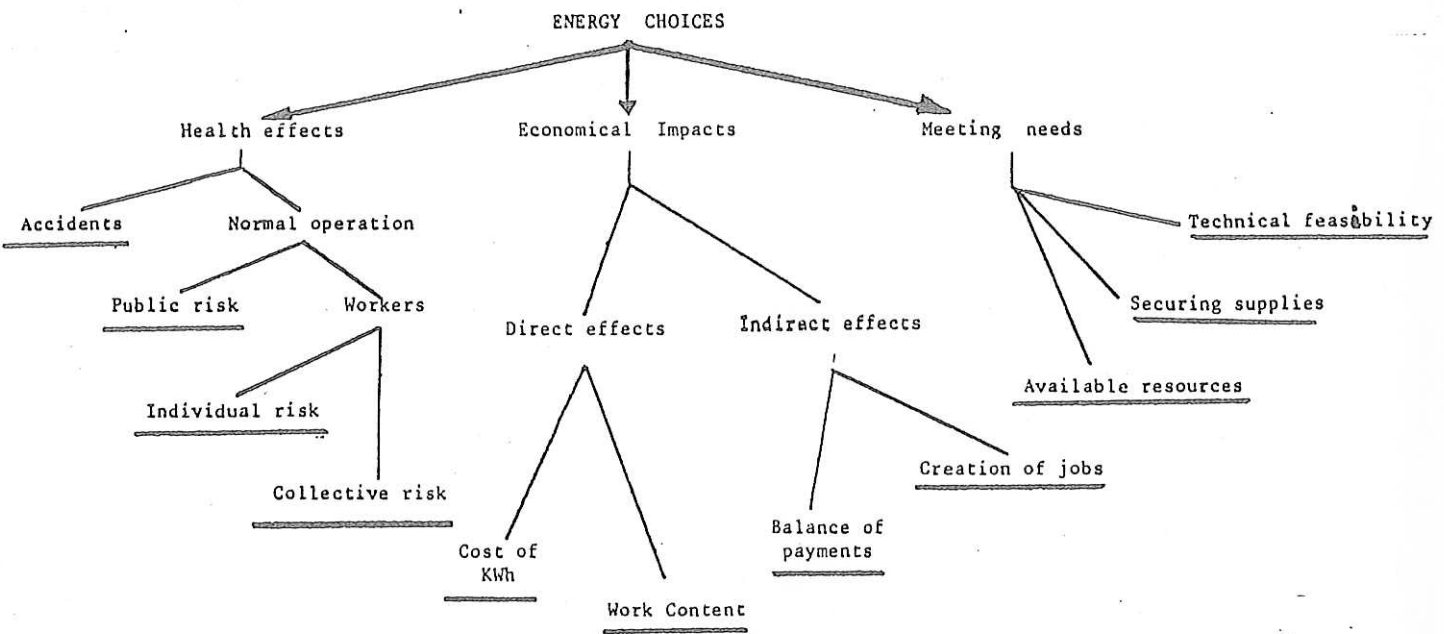


Figure 2 : Analysing implications of energy choices.

here : "available resources" is related to the energy potential of the source being considered. It could have been evaluated on a national level but it was more logical to consider it on a worldwide level. The second criteria derives from the first : to what extent could France depend on worldwide resources. The third criteria relates to feasibility from the purely technical point of view, without taking into consideration such factors as economic constraints. However, the adaptability of the techniques under consideration was not chosen as a criterion even though this was referred to in the Hugon Report. The decision to calculate the effects of technologies furnishing the major part of electricity needs made this unnecessary.

In the field of economics, we distinguished between direct and indirect effects. The postulates -the cost of a Kwh and the work content- can be interpreted directly. The second postulate is directly related to the technical efficiency of an energy chain : that is, what is the quantity of work necessary both for the construction and operation of an installation to produce one unit of energy. The other effects become clear only in a macro-economic context. This is the case of the effect on the balance of payments, which by itself is not very significant, and on the creation of jobs ; both can only make sense by using a macro-economic model. Another important effect, but which is more difficult to describe, was not taken into account : it is the effect on the industrial and social structure. Developing certain modes of energy production can lead to a restructuring of the economy, which is the case of many renewable sources of energy (see /2/).

The theme of risk is at once richer and more complex. The four criteria chosen have already been more or less aggregated. We confined ourselves to health risks for the population. In this analysis, the environment is considered only as the place where a transfer to man takes place. The first distinction is between normal operating conditions and accidents, and therefore between everyday risk and catastrophic events. In the case of the latter, we took only one criterion even though some authors prefer to distinguish very grave events with a very low probability from the others. So-called "normal" operation also involves risks both for the public via the emission of pollutants and for workers. In each case one can distinguish between the risk run by an entire population -the collective risk- and the risk for each exposed individual. The number of exposed persons varies with the

type of energy source, so that the criteria are not correlated. An other interpretation of these criteria can be expressed in is talking about "social cost" in the first instance or about equity in the second instance (see /23/). For the public, individual risk is relatively low and therefore difficult to interpret, and so was not taken into account but for workers, both criteria were kept.

It would be incorrect to state that all these criteria are absolutely independent : safety, or the risk of major accident, has an economic effect, being assured of steady supplies may affect prices, and so forth. Nonetheless the relations between the various criteria are rarely simple and are generally poorly understood. If a correlation exists, it is purely theoretical.

2.4. Presentation of the criteria

Here we shall proceed to describe the criteria, a synoptic view of which is presented in Table 3.

2.4.1. Collective occupational risk

This includes all effects on workers' health. The production of a given quantity of energy entails occupational accidents (deaths and injuries) as well as observable occupational illnesses. To this should be added other effects calculated with the use of theoretical models, such as the delayed effects of radiation. The figures given here were taken from /35/. We use an aggregated indicator ; the effects are calculated in Equivalent Number of Working-days Lost. The number of days lost per accident is aggregated to the number of deaths, on the basis of the following :
1 death = 6,000 e.n.w.l.

The criterion is "normalized" by the energy produced and is expressed in enwl's by Twh(*). Comparisons are then made : the smaller the value, the better the chain. Uncertainty is rather great and derives from the imprecision of the risk itself as well as from that of the number of workers needed to produce 1 Twh.

(*) Twh, a unit of energy. $1 \text{ Twh} = 10^9 \text{ Kwh}$.

2.4.2. Individual occupational risk

The preceding indicator is indeed the product of the number of workers multiplied by a risk. This can properly be called a social cost : in other words, what society is willing to pay indirectly for the production of 1 Twh, the number of working days lost being measured and defined by a system of social reparation (see /45/).

Individual risk measures the prejudice done to individuals ; it is quantified solely by a mortality rate (here, deaths per 1,000 workers). Injuries are obviously also harmful to the individual but their measurement is too biased to be included in the criterion (see /45/).

The difference between collective risk and individual risk can also be expressed in the following way : when there is a high collective risk and a low individual risk, one can say that the option has a high social cost but is good from the point of view of equity.

2.4.3. Public risk during normal operation

This is obtained by theoretical calculations that allow one to move from effluent releases to health effects. They are complex and open to great uncertainty. Effects of atmospheric pollution and radiological effluents can nonetheless be calculated. The values given here were taken from /5/ but a clearer idea of the uncertainties surrounding pollution can be gained from /69/ or of radiation effects from /36/.

The criterion is still "negative" ; to simplify comparisons, it is expressed in the same unit as criterion 1 even though health effects are almost always deaths.

2.4.4. Risks of major accident

Here, risk is graded from 0 to 5, a scale which presents catastrophic risks in a succinct fashion : the higher the grade, the greater the danger of the chain (this

method was suggested by Holdren /7/). Up till now, only the Rasmussen Report (see /51/) has gone thoroughly into the question of nuclear plants. However, it has not met with unanimous acceptance, and no equivalent exists for other chains. Nonetheless it is recognized that a major potential risk exists in refineries, and that serious accidents can occur in coal mines, not only inside the mine but on the surface as well, by the collapse of coal tips or the ground itself.

2.4.5. Technical efficiency : work content

Here, the quantity of work necessary to produce a unit of energy is measured. This seems like a straightforward criterion, and yet it has often been misconstrued. The Hugon Report (see /9/) draws attention to this point : the quantity of work is a criterion of technical efficacy and not an indicator of possible new jobs. The more work that is needed to produce a given good, the less the chain is efficient as a mode of production. The creation of new jobs should be given a separate criterion : for the moment , work content is a negative criterion : the higher it is, the worse the option.

The values used are taken from /35/ and are described at length in /32/.

The margin of uncertainty does not always have the same meaning. In the case of oil and coal, it can be attributed to the parameters of the scenarios ; in the case of nuclear power, it is attributable primarily to variants in calculations ; and in solar chains, it is the unknown factors in technical developments that explain the size of the interval.

2.4.6. Creation of jobs in France

Though it is often talked about, this subject has rarely been thoroughly explored. Some indications of potential jobs are given in the Hugon Report /9/ and in the reports of the VIII National Plan /12/, but a complete analysis, which would consist of entering all the parameters in a macro-economic model, has not yet been done. Other things being equal, one can conclude that there will be new jobs created if the cost of the KWh is lower or if the amount of foreign currency is less,

or yet again if the amount of work required is greater. The effects are beneficial for employment because the economy is performing better in the first cases or because there is a direct influence in the last case. Generally speaking, however, the effects are antagonistic : when work content is higher, costs generally tend to rise. A notable exception is that of oil ; because of rent the cost of a Kwh is high despite the fact that the work content is low. Using the data as well as more theoretical considerations (see /53/) we established a grading system for criterion 6 and the best chains are those with the highest grade.

2.4.7. Cost of Kwh

This simple criterion requires no particular remarks, except that it is well suited to the modelization of uncertainty. As far as solar chains are concerned, the cost depends primarily upon the way in which one extrapolates industrial installations from existing projects or prototypes (see /33/). The parameters of costs of conventional energies are more familiar ; they are summarized in Table II.

TABLE II : Cost of a Kwh under conditions prevailing on Jan. 1, 1981 (see /9/) unit : French centimes per Kwh.

	Nuclear	Coal	Oil
Investment	8.5	6.5	5.6
Operation	3	3.1	2.8
Fuel	4.2	15	43.4
Σ	15.7	24	51.8
Possible desulfurization		2.8	3.5

The largest unknown factor is the cost of fuel, which might double in the coming decade. Another unknown is of a juridical nature : desulfurization may become mandatory. The choice of a normative interest rate which allows one to calculate "investment" is also important, for advocates of new forms of energy often dispute this point. The way in which certain connected expenditures like prospecting, research, and monitoring the environment can also be disputed.

2.4.8. Balance of payments

This is a negative criterion, which is expressed in billions of French francs 1980 and is based on a 1990 scenario ; it therefore corresponds to a production of 300 Twh. A number of studies have examined this criterion (see /9/ and /12/). The cost raw materials is of course a factor here, but it is not alone. Solar energies for example, have a negative balance because, as in any industrial installation, some of the equipment is comported (see /41/).

2.4.9. Available resources

Constructing a criterion for available resources seems fairly simple, and yet it poses a delicate problem of logic : when comparing conventional chains with renewable energies, one must work with constraints expressed in terms of stored energy on the one hand and energy flows on the other.

Starting with a scenario of world electricity demand for the years 1985-2030 (see /19/), we built the criterion in the following way so as to see what portion could be filled by each energy chain. Having obtained annual needs and having decided that 5 % of the land would be used to capture solar energy, we wanted to see if solar chains could match annual demand : while there is a surplus till the year 2000, there is not enough afterwards. The total energy demand was easily compared to available stocks of conventional energy chains. It is worth noting that only coal meets more than needs (The figure is 1.5, meaning that the stored energy is half more than needs).

The uncertainty factor is given, but it is of course valid only if one accepts the rather special logic used here.

2.4.10. Secure supplies

This factor can only be judged subjectively, using geopolitical considerations. The Hugon Report does give a series of values (see /9/) but we have used our own interpretation. This criterion is presented as positive : it represents the percentage of chances that supplies will be maintained.

2.4.11. Technical feasibility

As certain chains exist but others do not, we had to give a value to this determining factor. To quantify it, we chose to use the number of years it would take to build up a large-scale industry for each of the options envisaged. Even when industrial prototypes exist, that lapse of time is very long, from five to ten years. This was the case of the Thek chain. The "Super Themis" plant that we imagined was even further from the present prototype, and we considered that a value of 15 years seemed plausible. As for the photovoltaic chain, there are only projections (see /33/), which explains the long lapse of time we choose. Apart from its own value, this criterion allows us to review the preceding criteria : it indicates the logic behind our calculations.

3. METHODOLOGY TO COMPARE ELECTRICITY-PRODUCING TECHNOLOGIES

3.1. Background to approaches

A good deal of the literature devoted to the comparative study of energy alternatives deals with the various methodological problems that render comparisons difficult (see especially /30/ and /21, 18/. The aim of most of these so-called comparative studies is to provide a strict framework for comparisons rather than to find a global answer. A few conventional or non-conventional sources of energy are chosen and then evaluated according to health impact and/or socio-economic criteria with no attempt to do an explicit aggregation of these criteria for comparative purposes (/6/, /7/, /25/, /27/, /28/, /44/, /56/, /62/, /63/, /64/, /67/).

Holdren and his team (/27/, /28/, /62/) try to do thorough an analysis of energy sources as possible by taking into account a large number of alternatives and evaluation criteria. For California (cf /27/), for example, Holdren presents a list of 22 alternatives evaluated according to 11 criteria on a scale of 0 (negligible impact) to 5 (worst impact). In the evaluation of technology impacts and environmental effects, the author's view is based on his own studies or on reports by other researchers. The values assigned to the risk of serious accidents/sabotage for the energies we are concerned with here are shown in Table 3.

Table 3 : Multicriteria evaluation of six energy alternatives.

	(*)	Oil	Coal	Nuclear P.W.R.	Super-Themis	Super-Theck	Photovoltaïque
1. Collective occupational risk (e.w.d.l. per Twh)	-	432 330 770	5 930 3 200 6 500	1 326 1 200 1 650	2 620 2 400 3 000	4 850 4 500 5 300	1 490 1 350 2 200
2. Individual occupational risk(deaths per 1 000 workers)	-	0.16 0.14 0.18	0.62 0.60 0.64	0.22 0.20 0.24	0.13 0.11 0.15	0.12 0.10 0.14	0.16 0.14 0.18
3. Public risk normal operation (e.w.d.l. per Twh)	-	4 000 2 000 6 000	2 000 1 000 4 000	100 10 300	1	1	1
4. Risk of major accident (see 2.4.4.)	-	4	1	5	0	0	0
5. Technical efficiency : work content (see 2.4.5)	-	140 100 250	460 250 500	325 300 400	974 900 1100	2 110 2 000 2 300	436 400 700
6. Creation of jobs in France (see 2.4.6)	+	1 0.9 1.1	4.5 4 5	5 4.5 5.5	5.1 4 6	4.3 3.5 6	7 5 8
7. Cost of a Kwh (see 2.4.7)	-	50 31 60	25 18 33	16 15 20	33.5 30 45	47 45 55	16.5 15 25
8. Balance of Payments (10 ⁹ F. per 300 Twh)	-	126 69 147	43.5 30 63	8.25 7.5 10.3	12.3 8 14	18.5 13 22	6 5 9
9. Available resources (see 2.4.9)	+	0.3 0.2 0.4	1.5 1.3 1.8	0.2 0.15 0.25	0.8 0.3 0.9	0.75 0.3 0.9	0.78 0.3 0.9
10. Secure supplies (% of chances that flow of supplies will not stop)	+	40 20 50	70 60 90	90 85 95	99 98 100	99 98 100	99 98 100
11. Technical feasibility (years for large-scale industrial build-up)	-	0	0	0	15 10 17	7 5 9	30 20 40

(*) - : The lowest figure indicates the best alternative.

+ : The highest figure indicates the best alternative.

The most common comparative technique to measure the environmental costs of emerging technologies is health effects assessment (/1/, /4/, /11/, /15/, /22/, /31/, /39/, /40/). This approach consists in doing a complete aggregation of all the health effects of a given energy by ranking them on a single numerical scale, be it monetary (having defined the cost of a human life) or social cost measured in working days lost. Comar and Sagan /11/, in particular, generate a comparative analysis of the health effects in terms of premature deaths and occupational injuries associated with the operation of a 1,000 MWe power plant, according to age brackets. The study concludes that occupational deaths due to coal are considerably greater than for the other technologies. There are likely to be more premature deaths from the use of coal and oil than from natural gas or nuclear fuel. Another study of this type, prepared by Inhaber /39/, was strongly criticized by many specialists ; it compared 11 technologies for the production of equivalent electrical energy (coal, oil, natural gas, nuclear, hydropower, solar thermal heating, methanol, wind, solar photovoltaic, solar space heating and ocean thermal) using the global indicator of "man-days lost per megawatt-year net energy output over the lifetime of the system". The study concludes that natural gas and nuclear energy are the least dangerous technologies and that the other non-conventional technologies are almost half as dangerous as coal and oil. This type of method presents two major drawbacks : first, the inherent uncertainty of each type of information on these technologies is not taken into account ; and, second, the aggregation of data related to different value systems and different scientific fields into only one dimension (the problem of incommensurability) shows up what Roy /50/ calls an instrumental bias, a classic phenomenon in optimization calculations.

Another approach used in comparative analyses which also runs into the same problem of incommensurability is cost-benefit analysis (/59/, /68/, /71/). Generally speaking, the studies in question set the benefits from a given economic activity against the losses. What is more, the price of a human life must be explicitly taken into account so that these two criteria can be aggregated. The USAEC study /68/, for example, monetizes health and safety impacts in order to estimate the total social cost (normalized to the annual energy produced by one 1,000 MWe unit operating at 75 % capacity) of coal, oil, gas and nuclear systems.

The ranking deduced from the values of these costs (expressed in $\$10^6/\text{year}$) is as follows : gas (0.5), nuclear (0.7), oil (1.1), coal (2.1). In addition to the fact that the treatment of uncertainty is inadequate and that non-quantifiable criteria have not been taken into account, "cost-benefit analysis has been classified as a decision framework that excludes all political, social and institutional considerations" (see /30/).

Some studies that have attempted to take so important a factor as uncertainty into account have used the decision analysis methodology based on the multi-attributed utility theory (see /8/, /23/, /46/ and /43/ for a more theoretical development). Though it seems to be a classic multicriteria method, this approach presents considerable operational complications, especially as far as assessment of probabilities and utilities attached to these criteria are concerned. The study done by Garriba and Ovi /23/ points up these difficulties : it compares four energy strategies (nuclear, coal, solar and "null" strategy) based primarily on socio-economic criteria. Whereas the optimal solution pruned (based on the maximization of the expected utility function) is the nuclear strategy, the sensitivity analysis that the authors develop later on completely contradicts the first results, for it gives the ecological strategy as the best action, which was ranked last in the earlier part of the study.

In their excellent recent overview, House and al /30/ describe a gamut of other methods that can also be applied to the problem of energy comparison. Among complementary methods, one should also mention the Delphi Technique, the Net Energy Analysis, the Indicators Analysis and the Multitechnology Approach.

The method that we present in the following section is based on the principle that evaluation criteria must retain their identity and their properties in the mechanism of a global comparison. Alternatives are compared two by two with the aid of a series of binary relations that are not deterministic but fuzzy so as to take phenomena of uncertainty into account. This multicriteria approach (see /73/ for an overview of multicriteria approaches) is based in part on a method of the French school which is partially compensatory, the ELECTRE Method.

3.2. The Multicriteria Methodology

We will use here, with a few minor changes, the methodology developed in /61/ which was the basis of a comparison of some 400 protection systems in French nuclear plants. A step-by-step diagram of how it works is shown in Figure 3.

The basic differences between this method and that presented in /61/ are : first, modelling of uncertainty phenomena on the level of a criterion is obtained not only from non-significant thresholds (see Table 3, criterion 2) but more generally from plausibility functions that can take any type of evaluation of a criterion into account ; and, two, in addition to the domination analysis in ranking techniques, we use the ELECTRE III algorithm of Roy /58/ based on a principle that is diametrically opposed to the first domination technique.

We shall now examine the successive steps in the method, using Figure 3 to guide us.

3.2.1. Monocriterion outranking relation

A few preliminary remarks and definitions are in order. A problem of multicriteria decision-making is usually formalized by means of a set of alternatives $A = \{a, b, c, \dots\}$ and a set of functions-criteria $\{g_1, g_2, \dots, g_n\}$; here the criteria are real-valued functions defined on set A so that $g_i(a)$ represents the performance or the evaluation of the alternative $a \in A$ on criterion g_i ; the higher the evaluation, the better the alternative satisfies the criterion in question. Consequently, the multicriteria evaluation of alternative a is the vector $g(a) = (g_1(a), g_2(a), \dots, g_n(a))$ comprised of partial evaluations of n criteria.

In Table 3 the evaluations of energy systems are not given in single values but in the form of intervals, that is, there is a modal value that is supposed to be the most plausible evaluation and, to its left and right, two values that represent the limits of the evaluation (see Figure 4, left-hand side). This type of evaluation of an alternative constitutes what is commonly known as a fuzzy number (see /16/, /17/ or /72/). A fuzzy number is also characterized by a membership function

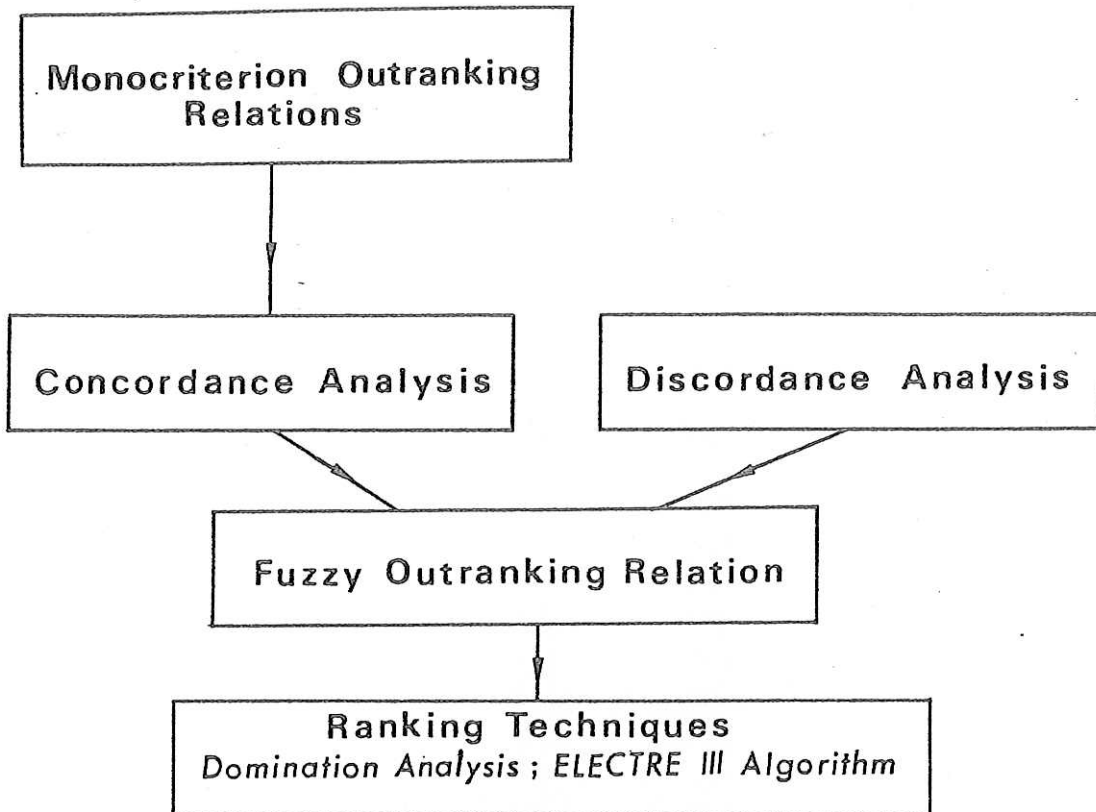


Figure 3 : Successive states of the methodology

$\mu_i : R \rightarrow [0,1]$ where $\mu_i(g_i)$ indicates by a number from 0 to 1 the plausibility of the evaluation of an alternative for each value of $g_i \in R$. As there is no information on these functions, we decided to represent them by linear segments, as shown in Figure 4, without a great loss of generality.

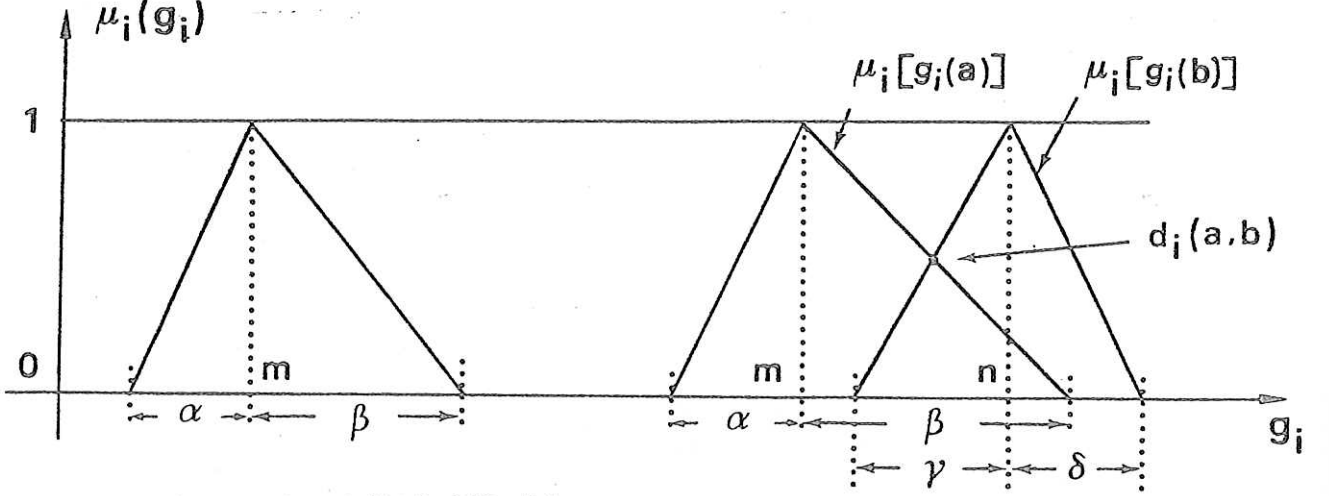


Figure 4 : Fuzzy number and the principle of comparison of fuzzy numbers.

Comparing evaluations, that is, of fuzzy numbers $g_i(a)$ and $g_i(b)$, means that the plausibility value (between 0 and 1) of the assertion " $g_i(a) \geq g_i(b)$ " must be made explicit or that an indicator $d_i(a,b)$ related to the comparison a versus b must be constructed. That allows us to define the structure of the monocriterion outranking relation. We should note in passing that, according to Roy /57/, the proposition "a outranks b" means that one is in a position to state that a is at least as good as b, and that the proposition "a does not outrank b" means the proofs to support the converse proposition are felt to be insufficient.

So as to make the idea of outranking operational, we propose here to assess the fuzzy outranking relation $d_i : A \times A \rightarrow [0,1]$ by applying Zadeh's extension principle /72/ to the comparison of fuzzy numbers. This gives :

$$d_i(a,b) = d_i[g_i(a), g_i(b)] = \sup_{g_i(a) \geq g_i(b)} \{\min(\mu_i[g_i(a)], \mu_i[g_i(b)])\} \quad (1)$$

More concretely, for two triangular fuzzy numbers of the type (m, α, β) and (n, γ, δ) (see Figure 4, right-hand side and Figure 5 for a numerical illustration) we find according to (1)

$$d_i(a,b) = \begin{cases} 1 & \text{if } m \geq n \\ 0 & \text{if } n < m \text{ and the two intervals are disjoint} \\ 1 - \frac{n - m}{\beta + \gamma} & \text{otherwise} \end{cases} \quad (2)$$

$d_i(a,b)$ is the degree of outranking of alternative b by alternative a on the i -th criterion. This indicator is supposed to be very optimistic, whereas a good many authors propose other indicators that can sometimes be very pessimistic (see /17/ for an overview on this point). In /61/, for the special case of thresholds, we use an indicator that is slightly less optimistic than (2).

3.2.2. Concordance analysis

This analysis, which is merely a simple majority rule presupposes that the relative importance of the criteria expressed by positive numbers $p_1, p_2, \dots, p_n$, whose sum is equal to 1, is given. The concordance analysis therefore consists in rendering explicit the fuzzy binary relation $C : A \times A \rightarrow [0,1]$, such as :

$$C(a,b) = \sum_{i=1}^n p_i d_i(a,b) \quad (3)$$

$C(a,b)$ represents in a manner of speaking the percentage of weights of the criteria that concord with the proposition "a outranks b".

3.2.3. Discordance Analysis

From here on, we shall call the modal value m of the evaluation for $g_i(a)$, $a \in A$, that is, the most plausible evaluation of a . We mentioned earlier that the great advantage of ELECTRE-type methods is that the comparison of alternatives is partial, given the fact that the criteria retain their intrinsic properties and can "refuse" certain comparisons (discordance effects). This phenomenon can occur in either direction for a given pair of alternatives (a,b) and can lead to the proposition "a is incomparable to b", in other words, there is non-outranking in either direction.

Suppose, in fact, that for (a,b) , we have $C(a,b) = 1$; this means that we have $g_i(a) - g_i(b) \geq 0$ for each i . On the other hand, for $C(a,b) < 1$, there is at least one criterion i^* , such as $g_{i^*}(b) - g_{i^*}(a) > 0$; if this inverse difference is too great and this beyond a veto threshold $v_{i^*}(g_{i^*}(b) - g_{i^*}(a) \geq v_{i^*})$, the proposition "a outranks b" is definitively refuted and criterion i^* is thus certainly discordant to this proposition. We shall subsequently see that this phenomenon globally corresponds to a nul outranking ($d(a,b) = 0$) ; thus if non-outranking occurs in the other direction as well, that is, $d(a,b) = d(b,a) = 0$, the two alternatives can be said to be incomparable. To illustrate this, let us take the example of oil and photovoltaic systems. If we consider that in a strategy for a short-term management of resources (see section 4), the veto thresholds for the two last criteria are respectively $v_{10} = 50$ and $v_{11} = 7$, the two systems become incomparable when differences of evaluation are compared with these thresholds (see Table 3). In this strategy, oil proves to be too unreliable while the photovoltaic system is too utopian.

Modelling of discordance in the face of uncertain evaluations can be obtained by using n veto thresholds v_i and n fuzzy discordance relations $D_i : A \times A \rightarrow [0,1]$ with :

$$D_i(a,b) = \begin{cases} 1 & \text{if } g_i(b) - g_i(a) \geq v_i \\ 0 & \text{if } g_i(b) - g_i(a) \leq s_i \\ \frac{g_i(b) - g_i(a) - s_i}{v_i - s_i} & \text{otherwise} \end{cases} \quad (4)$$

where s_i is the maximum spreading of evaluations on criterion g_i (cf, maximum of α and β , Figure 4) and $D_i(a,b)$ is the intensity of discordance of criterion g_i for the proposition "a outranks b" ; for $D_i(a,b) = 1$, this discordance is certain and gives, as showed above, $d(a,b) = 0$.

3.2.4. Fuzzy outranking relation

This fuzzy relation, designated as $d : A \times A \rightarrow [0,1]$, can be seen as an amalgamation of the concordance analysis and the discordance analysis that we have

just developed. It gives a degree of overall outranking of one alternative by another, but it leaves the analyst a good deal of freedom to define its analytical form, using concordance and discordance relations. In the preceding development of discordance, we gave the two extremes between outranking and non-outranking, that is, that outranking is certain ($d(a,b) = 1$) when there is a perfect concordance ($C(a,b) = 1$) and that non-outranking is certain ($d(a,b) = 0$) when at least one criterion i^* is certainly discordant to the outranking ($D_i(a,b) = 1$). These ideas provide a clear explanation for the analytical formulae given below, which also include all intermediary cases.

$$d(a,b) = \begin{cases} C(a,b) & \text{if } C(a,b) \geq D_i(a,b) \forall i \\ \frac{C(a,b)}{1-C(a,b)} \prod_{i^*} [1-D_{i^*}(a,b)] & \text{with } i^* \in \{i/D_i(a,b) > C(a,b)\} \end{cases} \quad (5)$$

with $d_i(a,b)$, $C(a,b)$ and $D_i(a,b)$ defined respectively by formulae (2), (3) and (4). The second formula in (5) allows us to take into account only the most significant discordancies in the calculation of $d(a,b)$.

3.2.5. Ranking techniques

A ranking procedure should be derived from the outranking relation defined above. Several traditional methods use more or less sophisticated metrics to assign alternatives to ordinate classes, but these techniques often are difficult to use.

To handle the energy problem, we choose two procedures based on very different principles :

- The first is based on the notion of transitivity of fuzzy relations (see /52/) and consists in calculating for each alternative an indicator that reflects the non-domination degree of the alternative simultaneously by all the others. This indicator, which varies from 0 to 1, is given in the formula below (6) :

$$\mu^{ND}(a) = 1 - \max_{b \in A} [d(b,a) - d(a,b)] \quad (6)$$

The result is that the higher the non-domination degree, the more preferable is the alternative. Nonetheless, this technique cannot rank order all the elements of A

simply because it is non-compensatory ; on the other hand, it can prescribe choice priorities, especially when $\mu^{ND}(a)$, $a \in A$ is close to 1 (see /61/ for further details).

- The second ranking technique is Roy's ELECTRE III algorithm /58/, based on the notion of qualification indicator $q(a)$, $a \in A$ which is equal to the difference $p(a) - f(a)$, with $p(a)$ being the number of alternatives to which a is strictly preferred and $f(a)$ being the number of alternatives which are strictly preferred to a . In order to count the alternatives starting from a fuzzy relation, Roy introduces a sufficiently small threshold λ so as to be able to discretize the range of values of $d(a,b)$ between 0 and 1. He then defines the first class of the descending weak order C_1 by maximizing the qualification over A ; he repeats this process, starting with $A - C_1$, and so on. The algorithm proceeds to build a second, ascending, weak order, starting this time with the last class, which corresponds to the minimal level of qualification. The result is finally the intersection of these two weak orders which, because it is a transitive partial order, points up a fair number of pairs of incomparable alternatives.

4. APPLICATION AND RESULTS

4.1. Preliminary Steps

Following the methodological plan outlined in Figure 3, we obtain for the data in Table 3 the 11 monocriteria outranking relations (see Table 4 and appendix). So as to give a complete numerical illustration of the formulae (2), we present in Figure 5 the six plausibility functions for criterion g_7 , "the cost of a Kwh" and the resultant $d_7(a,b)$ outranking (Table 4).

		Oil	coal	Nuclear	Themis	Thek	Photov.
$d_7(a,b) =$	Oil	1	0,074	0	0,459	0,889	0
	Coal	1	1	0,182	1	1	0,452
	Nuclear	1	1	1	1	1	1
	Themis	1	0,261	0	1	1	0
	Thek	1	0	0	0	1	0
	Photo-voltaic	1	1	0,909	1	1	1

TABLE 4 : Outranking Relation of the "Cost of a Kwh" criterion.

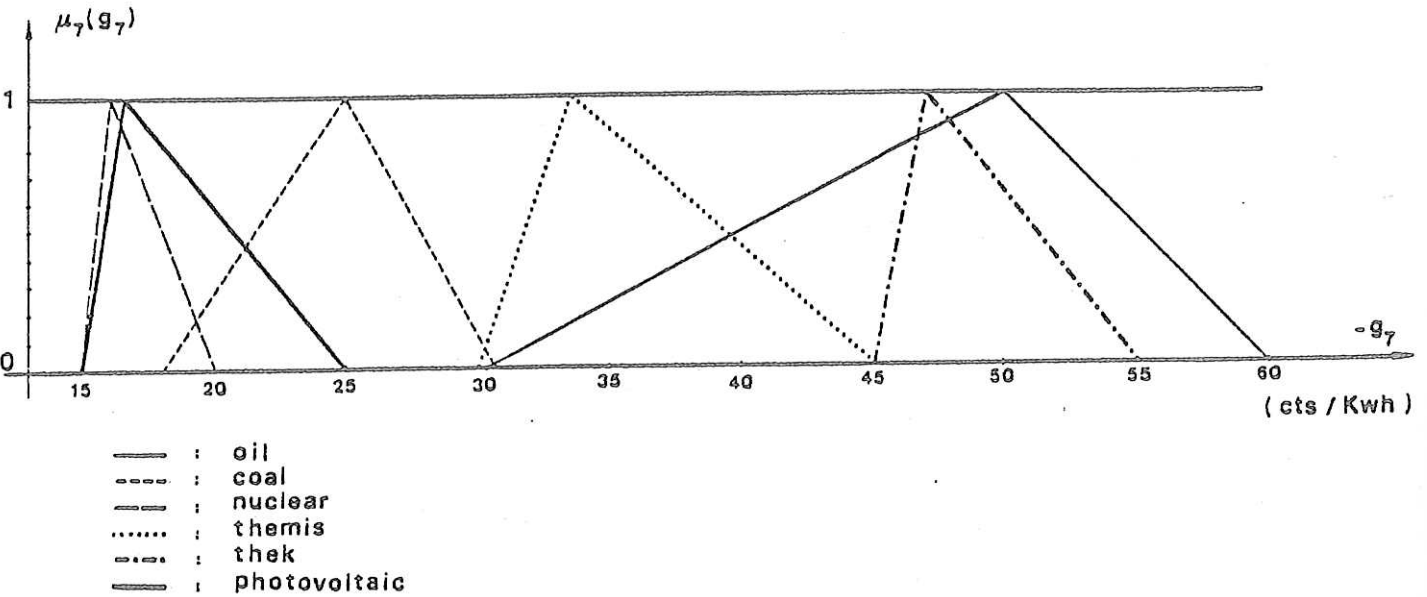


Figure 5 : Plausibility functions related to "Cost of a Kwh" criterion g_7 .

To perfect the rest of the steps in the method, one must establish the weights and veto thresholds for the 11 criteria. As we pointed out in section 2.2., the comparisons of energies has to be done within the framework of four strategies, each one representing a very different energy policy and which therefore has different weightings and vetos. It should be noted that there is a relation which is not necessarily functional between the weight and the veto threshold of a criterion : when the weight of a criterion becomes increasingly great in the decision process, the veto decreases, and vice versa.

4.2. Definition of strategies

At this stage, it proved necessary to re-examine the political parameter to obtain the gamuts of weighting that express conflicting strategies. The most obvious solution would have been to question those involved, but this was not done for several reasons. For one, public opinion is difficult to measure in this field (see /65/) and, what is more, the criteria we choose are emotionally charged. The public often uses these themes to express a system of values (see /20/), and circumspection should be shown when trying to interpret the results of inquiries. The same is true when one tries to find out what decision-makers think : someone in a position of responsibility cannot allow himself to describe his weighting system openly and he usually tries to show that he is sensitive to what the public thinks (see /66/). Would anyone badly state that safety is a secondary consideration or that employment is not really important ? However, the stands taken by these various groups are well known, and a hierarchy of criteria is implicit in press declarations, in various reports put out by the government or by enterprises active in the energy field, in parliamentary debates and in ecologist criticisms.

In fact, it was fairly easy to construct four sets of criteria and to define veto thresholds by referring to each group's habitual stand. Four strategies were thus chosen, which correspond to four quite typical points of view.

For the sake of clarity, we divided the weighting process into two steps. The weights were first given for groups of criteria : health effects, safety, the economy, meeting needs and technical feasibility (see Figure 2). Next, each of these groups was weighted, and the weights were refined within each group (see Table 5).

It is worth noting that when a similar experiment was made in /26/ on protection systems, specialists in quite different fields were in agreement. We thus took advantage of this previous experience, with one exception : we did not pursue the comparison by means of sensitivity analyses, which sometimes render the hypotheses somewhat restrictive from the practical point of view.

4.2.1. The point of view of an economist

In this strategy, we tried to stay as close as possible to economic thinking and keep within a short-term view. The two most important (most heavily weighted) groups are naturally the economy and technical feasibility. Safety and needs to be met are also significant, for both have economic impacts. Naturally, weight is especially important in the case of technical feasibility ; available resources are above all a long-term criterion. As for health impacts, they primarily concern workers. The risk they run is indeed a direct economic cost, since compensation is given for accidents and occupational illnesses.

TABLE 5 : Weights and veto thresholds of the criteria (weights are reduced to a sum equal to 1).

Criteria	Strategy 1		Strategy 2		Strategy 3		Strategy 4	
	weight	veto	weight	veto	weight	veto	weight	veto
1	0.04	10 000	0.075	10 000	0.05	7 000	0.0075	9 000
2	0.005	2	0.03	2	0.04	1	0.0225	2
3	0.005	10 000	0.045	10 000	0.01	10 000	0.12	9 000
4	0.1	10	0.1	10	0.1	15	0.1	10
5	0.04	8 000	0.18	4 000	0.02	10 000	0.48	5 000
6	0.12	10	0.015	20	0.01	22	0.06	30
7	0.12	60	0.09	70	0.3	30	0.03	45
8	0.12	150	0.015	300	0.07	100	0.03	250
9	0.015	5	0.32	2	0.01	10	0	∞
10	0.135	50	0.08	100	0.09	50	0.1	100
11	0.3	7	0.05	100	0.3	10	0.05	20

4.2.2. Strategy of long-term resource management.

The two extreme weights characterize this strategy, a 0.4 weight being given to the group of criteria response to needs and 0.05 being to technical feasibility. Obviously, the criterion available ressources is much more important than secure supplies in the meeting needs group. The fairly important weights assigned to health impact on the population, including safety (seen this time as harm done to the public), can be traced to the ecological sensibility of those who are concerned with long-term management of resources. The tie-up here is more

ideological than logical. Indeed the values given to vetos remain high for these criteria. It is not surprising that economic criteria remain highly weighted, and even the cost. That is because a high cost represents a waste of human resources or of a scarce product. Moreover, our method for calculating costs, based on extrapolations for industrial installations, penalizes new energies less. Those who prone management of scarce resources usually feel that present-day costs, based on prototypes make no sense.

4.2.3. Strategy of the electricity producer

Two themes predominate : technical feasibility and the economy. In the second group , the cost of a Kwh is the most important criterion, although the balance of payments is also significant because the producer has to integrate State constraints and, moreover, he himself has to pay in foreign currency. Anything that might adversely affect production also enters in, that is to say, secureness of supplies and safety of the installations. However, a rather high veto is attached to the last criterion for it reveals a certain amount of incredulity as far as a scale of risks is concerned. A producer expends a great deal of effort to reduce catastrophic risks and he believes that the safety level is adequate. Health impacts on the public and on workers also enter in. Too high a risk for the public would lead to difficulties in setting up production units ; too high a risk for workers would produce a good deal of tension in the company. It should be noted that this strategy is slightly exaggerated, for we imagined a producer who took only his own interests into consideration. In France, at least, as electricity production is a public service, it is likely that the weighting would be different, especially as national goals are part of the company's strategy.

4.2.4. Strategy of local politics

This weighting may seem rather curious but it does take the concerns of local elected officials into account. Many of the speeches made during the debate in the French parliament are reflected in this strategy. A first particularity is the weight of the criterion of technical efficiency. But what is important above all is that it is read backwards. It is, in fact, assimilated with new jobs created : the less

efficient a chain, the more workers are needed to run it. On the national level, this sort of reasoning is absurd, because in one way or another an inefficient chain will adversely affect the economy. But on the local level, where the installation is being built, such considerations do not enter in.

One should also note the small weight assigned to technical feasibility. So long as an installation is being built, it does not matter much whether it is a prototype or a profitable installation. Similarly, the availability of resources on the long term is not a concern of local officials.

4.3. The comparison stage

When the method outlined in Figure 3 is applied, we obtain four fuzzy outranking relations (see Table 6), each of which corresponds to one of the four strategies defined above. Two ranking techniques (domination analysis and ELECTRE III, see section 3) were used to treat these relations, and the respective results appear in Table 7 and Figure 6. Although these last rankings were based on realistic hypotheses to give an idea of a global comparison of six alternatives, it was at times absolutely necessary to examine the outranking relations that supplied the most information, since they provided comparisons by pairs of alternatives. We shall now examine the results for each strategy separately.

Strategy 1 : The point of view of an economist

The special characteristics of this strategy result in the fact that some criteria (notably the utopian criterion 11) with relatively low veto threshold nonetheless act as constraint. This obviously leads to a large number of incomparabilities which especially affect pairs : solar energies versus conventional energies. This is shown by the presence of many zeros in Table 6. The energies favoured in this strategy are therefore nuclear and coal ; they respectively have non-domination degrees of 1 and 0.660 (see Table 7) ; the other degrees are well below 0.5.

The ELECTRE III algorithm (Figure 6) gives a similar ranking but there is additional information : the Thek and Themis solar systems prove to be incomparable to the photovoltaic system and all of them are incomparable to coal. On the other hand, the nuclear chain unquestionably appears to be the best short-term system for producing electricity.

TABLE 6 : The fuzzy outranking relations obtained for the energy strategies. To calculate discordancies, we took : s_1 : 2730, s_2 : 0.02, s_3 : 2000, s_4 : 0, s_5 : 264, s_6 : 2, s_7 : 19, s_8 : 57, s_9 : 0.5, s_{10} : 20 et s_{11} : 5.

	Strategies	Oil	Coal	Nuclear	Themis	THEK	Photov.
1	Oil	1	0.396	0	0	0	0
	Coal	0.915	1	0.545	0.550	0.619	0.407
	Nuclear	0.805	0.885	1	0.733	0.740	0.572
	Themis	0	0	0	1	0	0.581
	THEK	0	0	0	0.661	1	0.563
	Photov.	0	0	0	0	0	1
2	Oil	1	0.305	0.755	0.352	0.408	0.322
	Coal	0.715	1	0.605	0.649	0.701	0.581
	Nuclear	0.402	0.580	1	0.368	0.370	0.339
	Themis	0.695	0.383	0.595	1	0.942	0.628
	THEK	0.695	0.352	0.585	0.613	1	0.610
	Photov.	0.695	0.630	0.735	0.917	0.920	1
3	Oil	1	0.353	0	0	0	0
	Coal	0.890	1	0.498	0.636	0.671	0.465
	Nuclear	0.783	0.890	1	0.749	0.750	0.700
	Themis	0	0	0	1	0.690	0.560
	THEK	0.630	0.351	0	0.566	1	0
	Photov.	0	0	0	0	0	1
4	Oil	1	0.104	0.053	0.016	0.014	0.007
	Coal	0.970	1	0.685	0.102	0.106	0.544
	Nuclear	0.870	0.672	1	0.105	0.089	0.063
	Themis	0.942	0.928	0.893	1	0.464	0.879
	THEK	0.942	0.915	0.863	0.920	1	0.874
	Photov.	0	0	0	0.276	0	1

TABLE 7 : Non-domination degrees by strategy (optimal alternatives are preceded by an asterisk).

Energy alternatives	Strategy 1	Strategy 2	Strategy 3	Strategy 4
Oil	0.195	0.590	0.217	0.071
Coal	0.660	0.951	0.608	0.174
Nuclear	(*)1.000	0.604	(*)1.000	0.212
Themis	0.267	0.710	0.251	0.545
Thek	0.260	0.651	0.251	(*)1.000
Photo-voltaic	0.419	(*)1.000	0.300	0.126

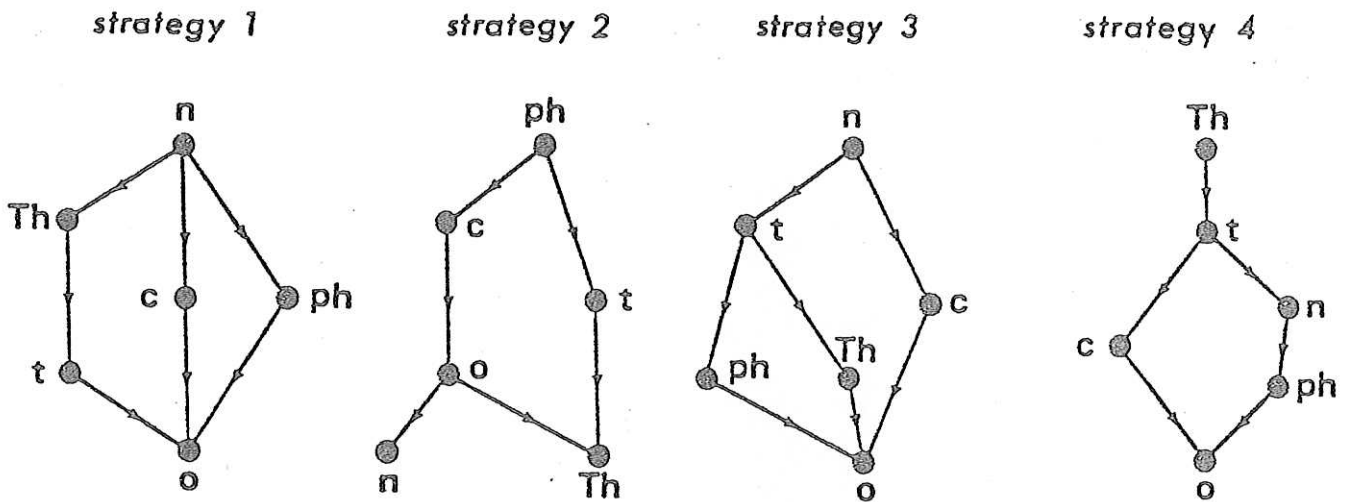


Figure 6 : The partial weak orders of the ELECTRE III Algorithm
(o : oil, c : coal, n : nuclear, t : Themis, Th : Thek,
ph : photovoltaic, discretization step $\lambda = 0.05$).

Strategy 2 : long-term management of resources

The constraints referred to earlier are practically done away with in this second strategy (see Tables 5 and 6). The ranking algorithms work in such a way that the electricity-producing system of the future turns out to be the solar photovoltaic. The fact that the non-domination degrees in Table 7 are more or less close they vary from 0.59 to 1.00 leads us to think that the domination of the photovoltaic system is not very strong. Moreover, the partial order of ELECTRE III shows that the Themis system is not comparable to oil and coal chains. Only one contradiction appears, however, vis-à-vis the first method : oil is in a better position than either the nuclear or the Thek system.

Strategy 3 : The strategy of the electricity producer

The system of veto thresholds specific to this policy produces roughly the same configuration of the outranking relation as that in the first strategy (see Table 6). In terms of non-domination degrees, this is expressed by exactly the same ranking as for the short term, that is to say, $\mu^{ND}(\text{nuclear}) = 1$, $\mu^{ND}(\text{coal}) = 0.6$ and all the other systems with very low degrees (less than 0.3). Yet the second algorithm (Figure 6) is such that the three solar chains cannot be considered as comparable to the coal chain.

Strategy 4 : strategy of local politicians

This special strategy favors in particular technical efficiency (see 4.2) of an energy chain ($p_5 : 0.48$, Table 5) ; but here this criterion is defined in a positive way, that is, the best chain corresponds to the maximum work content. Is therefore seems perfectly natural that, at the top of the ranking produced by the two algorithms, one finds the solar thermal Thek system, whose work content is from 2,000 to 3,000 men x years for 1 Thw (see Table 3). A second system which seems interesting from the point of view of this policy is the Themis solar tower-type plant, but the degree of non-domination is 0.545.

Before concluding, it is worth noting that the oil chain does not hold much

interest in any of the four strategies envisaged ; indeed, in all the rankings obtained, oil practically comes in last of the six alternatives compared.

5. CONCLUSION

Recalling the aim of the analysis is worth while at this point. The electricity-producing energy alternatives were selected not with a view to optimization of a system but as a choice of a principal chain. Though this may seem fairly restrictive, the fact is that France has had to periodically make just this kind of choice since the Fifties. And successive answers have been found, depending upon the economic and strategic conditions at the time. First hydro-electric power was developed, and then it was the turn of coal, followed by the French nuclear chain. The latter was halted in favor of oil, to be followed by a new departure for nuclear energy, this time under a Westinghouse licence. The number of successive stages is sufficient to show the multiplicity of determining factors in energy choices. The diversity of arguments put forward and the heated and sometimes rather confused debate emphasize the complexity of decision-making in that field .

The first step in this study consisted in formalizing the problem. We tried to extract from a set of sometimes contradictory arguments the criteria that were actually taken into consideration when reaching a decision. The same themes keep cropping up : the economy, employment and harmful effects on the population. What differs, however, is the interpretation. The most striking example is that of work content, which is seen either as creating new jobs or else from the point of view of technical efficiency. In this respect our viewing of the question has improved during the process of formalizing a multicriteria analysis. Moreover the criteria finally selected allowed a fairly accurate interpretation of the positions of the various social groups involved. In this connection, we selected four strategies based on very different policies ; for each one, we favored the appropriate criteria.

In the framework of a comparative analysis, we developed a method which, instead of turning all the homogenous or heterogenous criteria into a single criterion for the sake of aggregation, allows us to keep their identity and intrinsic properties

while at the same time taking into account the uncertainty of the evaluations. The results coincided quite well with what we knew of these groups' stands on the question. The study also pointed up various possibilities for a compromise : coal was in a good position in many of the analyses. Despite the fact that it is talked about a good deal, it is interesting to note the risk criteria do not play a big role in the multicriteria analysis. On the other hand, attitudes vis-à-vis the long term plays a determining role. This kind of observation was one of the most interesting results of this analysis, for it provides a solid basis on which to reinterpret present-day conflicts. From this point of view, the method we propose may seem like a way to discuss or justify past choices, but its usefulness is in fact much greater. More and more questions are being asked in debates, especially about the so-called "new energies", for which little information is available to compare them with conventional energy systems. This method may then become tool for a decision-aid.

This study opens up two new perspectives, on the theoretical and practical levels :

- On the theoretical level, the use of the same multicriteria model allows us to do an analysis no longer of alternatives for choosing a single chain but of combinations of chains. This allows a more complex and realistic plane of comparison and lets the method play its role more fully.

- On the practical level, this method allows us to envisage strategies, and consequently data, for the various parties involved in the decision processes. We can then point up the sources of conflict on the level of results and ease negotiations.

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Appendix : Monocriteria outranking relations $d_1(a,b)$;
 $d_7(a,b)$ is given previously in table 4.

Criteria		Oil	Coal	Nuclear	Themis	THEK	Photo-voltaic
1	Oil	1	1	1	1	1	1
	Coal	0	1	0	0	0.611	0
	Nuclear	0	1	1	1	1	1
	Themis	0	1	0	1	1	0
	THEK	0	1	0	0	1	0
	Photov.	0	1	0.647	1	1	1
2	Oil	1	1	1	0.250	0	1
	Coal	0	1	0	0	0	0
	Nuclear	0	1	1	0	0	0
	Themis	1	1	1	1	0.750	1
	THEK	1	1	1	1	1	1
	Photov.	1	1	1	0.250	0	1
3	Oil	1	0.500	0	0	0	0
	Coal	1	1	0	0	0	0
	Nuclear	1	1	1	0	0	0
	Themis	1	1	1	1	1	1
	THEK	1	1	1	1	1	1
	Photov.	1	1	1	1	1	1
4	Oil	1	0	1	0	0	0
	Coal	1	1	1	0	0	0
	Nuclear	0	0	1	0	0	0
	Themis	1	1	1	1	1	1
	THEK	1	1	1	1	1	1
	Photov.	1	1	1	1	1	1
5 (+)	Oil	1	1	1	1	1	1
	Coal	0	1	0.526	1	1	0.949
	Nuclear	0	1	1	1	1	1
	Themis	0	0	0	1	1	0
	THEK	0	0	0	0	1	0
	Photov.	0	1	0	1	1	1

Appendix (continued)

Criteria		Oil	Coal	Nuclear	Themis	THEK	Photo-voltaic
5(-)	Oil	1	0	0	0	0	0
	Coal	1	1	1	0	0	1
	Nuclear	1	0.526	1	0	0	0
	Themis	1	1	1	1	0	1
	THEK	1	1	1	1	1	1
	Photov.	1	0.949	1	0	0	1
6	Oil	1	0	0	0	0	0
	Coal	1	1	0.500	0.625	1	0
	Nuclear	1	1	1	0.938	1	0.200
	Themis	1	1	1	1	1	0.035
	THEK	1	0.909	0.682	0.714	1	0.027
	Photov.	1	1	1	1	1	1
8	Oil	1	0	0	0	0	0
	Coal	1	1	0	0	0	0
	Nuclear	1	1	1	1	1	0.400
	Themis	1	1	0.362	1	1	0.137
	THEK	1	1	0	0.139	1	0
	Photov.	1	1	1	1	1	1
9	Oil	1	0	1	0.167	0.182	0.172
	Coal	1	1	1	1	1	1
	Nuclear	0.333	0	1	0	0	0
	Themis	1	0	1	1	1	1
	THEK	1	0	1	0.923	1	0.952
	Photov.	1	0	1	0.968	1	1
10	Oil	1	0	0	0	0	0
	Coal	1	1	0.200	0	0	0
	Nuclear	1	1	1	0	0	0
	Themis	1	1	1	1	1	1
	THEK	1	1	1	1	1	1
	Photov.	1	1	1	1	1	1
11	Oil	1	1	1	1	1	1
	Coal	1	1	1	1	1	1
	Nuclear	1	1	1	1	1	1
	Themis	0	0	0	1	0	1
	THEK	0	0	0	1	1	1
	Photov.	0	0	0	0	0	1