Mike- this is a paper I used when teaching environmental geology - it explains Delphi - & gives an example D.F.

GL01371 Environment

45. Energy and the Environment— A Delphi Forecast

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The first international long range forecasting study, *Energy and the Environment*, is a response to the need for a complex, yet relatively concise overview of potential developments in energy industries and their multitudinous environmental impacts. While specialized engineering analyses of past trends abound, and descriptions of environmental consequences of energy production have become increasingly common in the last few years, broad, long range inquiries into the future of energy and the environment are still rare.

Although necessary as a base, it was felt that any attempt to fill this gap could not be based just on a summary and evaluation of the piecemeal information widely scattered through the many current publications dealing with energy and environment. A complex and original long range forecasting study seemed to be needed. The Delphi forecasting method was employed successfully in this project, where 40 experts from seven nations participated in three rounds of questioning lasting almost a year. Delphi provided results in four separate, though highly interrelated, areas of interest. Percentage probabilities of five environmental episodes involving energy industries—urban air pollution, power supply failure, jumbo tanker wreck, offshore drilling oil spill, nuclear radiation contamination—were estimated for the 1970's. A relative ranking of the 25 most important energy-environment problems was established by the iterated Delphi procedure and future growth limits of seventeen contemporary technologies were forecast by the energy systems experts. The most important part are long range probability forecasts of 30 energy production, transmission and transportation technologies and 31 environmental protection, planning and management innovations.

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PROCEDURE

Since the mid-sixties the Delphi technique has acquired a good standing among forecasters and long range planners. George A. Steiner[1] in his comprehensive work on top management planning rates the Delphi as the most reliable of the technological forecasting methods. Dalkey[2] estimated well over 100 practical applications by mid-1969. John McHale[3] found during his typological survey of future research in the United States that the Delphi is the second most widespread method in American futuristics (scenario building used by 45 organizations, Delphi by 41, simulation gaming by 29, etc.). Delphi has been most widely used in military forecasting—both classified and unclassified; it has been widely implemented in corporate planning and in medical disciplines. Other published or announced applications cover a wide spectrum: business forecasting, civil defense policy, computer developments and applications, education innovation, evaluation of research projects, foreign affairs forecasting, information processing and social planning at community level (see comprehensive bibliographies of Turoff[4] and Pill[5]).

This fast adoption of the technique best testifies to its value for both technological and social forecasting. Most of the by now abundant literature finds in this method a powerful tool in the ever more increasing search for responsible decision-making. Criticisms of the Delphi among those who understand the technique well are infrequent and rather restrained. For example, a basic charge against the Delphi by R. E. Overbury[6] challenges the design of a forecasting exercise more than the value of the technique itself. Also, J. Pill in his recent critique is concerned more with the formal characteristics of the method than with questioning the validity of opinion eliciting in 'soft' areas. Though the method is generally well accepted and appreciated, some critical factors in its design, use and evaluation deserve closer examination. Only then can the Delphi results be fully understood.

GENERAL PROPERTIES

Delphi is a useful extension of systematic analysis into the areas of opinion and value judgments. It counters the limitations of traditional quantitative analysis, and opens up new horizons for more rational decision-making.[7] Evaluating probabilities and significance of various possible or desirable future developments, it offers new options for a planner. There appears to be hardly any other way to get these important, probabilistic yet definite answers. Respecting dissenting opinions, Delphi tries to arrive at a reasonable group consensus by iteration, but it is not just another kind of polling scheme. Opinion polls do not use iterative questioning with information feedback and do not present final results in the form of group consensus.

Delphi is not a decision tool—it is an analysis tool. Delphi output is still only an opinion, with no check for accuracy. There is no way to guarantee or control a specified outcome. It is an open-end analysis. Results are either accepted or suppressed. The decision maker can base his judgment on the Delphi results, but he alone must select a particular strategy and set goals and targets. People, not techniques, make decisions. Delphi's domain is intuitive forecasting. Its application is most useful and logical in complex areas where there exist uncertainty, doubt or disagreement, where there is seemingly no way to build any sort of model and where the results cannot be immediately confirmed or verified.

RESPONDENTS

Delphi is an exercise in opinion and value judgments—and the best results cannot be gained without the participation of people whose opinions and judgments are based on an extensive knowledge of subject. It is, of course, impossible even in topically restricted studies, to enlist the help of many participants who would be highly competent in all areas of a particular study. Selection of participants for this Delphi exercise was doubly hard due to the demands of the study. Massive scanning of the leading energy, environmental and general scientific journals and publications preceded the final choice of potential respondents. People with expertise in particular fields, but also familiar with and interested in broader issues of the current energy-environment scene were given explicit preference over narrowly oriented specialists.

Table 1 gives a detailed breakdown of respondents according to their specializations.

As for their affiliations, 8 were with government agencies, 6 with universities, 11 in editorial offices of specialized periodicals, and 15 in industry or industrial research. Among those who responded to a request for a few personal facts in the final questionnaire, 48 per cent have Ph.D. or other doctoral degrees, 37 per cent have various masters degrees and 15 per cent, bachelors degrees. Both the average and median number of years of experience in the profession was 21. Twenty-eight participants were Americans, 11 were Europeans (3 from the United Kingdom; 3 from France, 2 from West Germany; 2 from Switzerland; 1 from Belgium) and 1 Japanese.

Changes in panel composition between rounds could affect the outcome of questioning. But they would have to be rather significant shifts in participations which is not usually the case. In this Delphi about two-thirds of the respondents answered all three rounds, with more than 30 respondents in each round. This high stability guaranteed that the outcome was not adversely affected by participation fluctuations.

RESULTS

A great advantage of the Delphi method is the possibility of presenting the results of a complicated intuitive forecasting process in a

TABLE 1. PARTICIPANTS IN THE DELPHI STUDY ENERGY AND THE ENVIRONMENT

Specializations	Round 1	Round 2	Round 3	Total
Energy systems—general	12	11	11	14
Coal industry	3	4	3	4
Oil industry	5	5	3	5
Natural gas industry	1	1	1	1
Nuclear industry	2	3	3	3
Environmental protection	4	5	5	6
Air pollution	4	3	4	5
Nuclear radiation	1	2	2	2
Total	32	34	32	40

simple, easily comprehensible way. The outcomes of long range forecasting are shown as the quartiles and median of the 'break-even' time, the period when the innovation has a 50 per cent chance of occurring [Figure 1, Table 2]. For example, when the break-through time for fast breeders is given as 1981-1985-1990, it means that 25 per cent of respondents believed that there is a 50 per cent chance for breeders to become practically implemented before the year 1981, while 25 per cent of respondents saw this possibility only after the year 1990. The middle 50 per cent of participants believed that the period of break-through success for breeders is between 1981 and 1990, with the median date in 1985. Events are ordered according to the median date; if the median dates of two or more items are equal, the event with the earlier lower quartile date comes first.

In interpreting the replies, it should be recognized that the respondents used their own definitions of feasibility. Many may have considered only technical feasibility. However, this is not a sufficient criterion. Many processes may not be economically viable even if a broad concept is employed. Economists have long recognized that the market may neglect some costs such as pollution or benefits such as pollution abatement of different activities. After these costs and benefits are recognized, it may still be true that some technically possible activities may not be socially profitable.

In any case, the study was characterized by a fairly high degree of consensus. Excluding those estimates whose upper quartiles extend beyond the year 2020 (17 cases), the consensus was excellent (less than 10 years interquartile range) in six cases, very good (10-14 years range) in 18, good (15-19 years) in 13 and unsatisfactory (interquartile range 20 years or above) only in seven cases. Quartile range, a convenient measure of opinion spread, narrowed down during the iteration quite considerably. While the average range was 29.6 years after the second round, it decreased by more than half to 12.2 years after the final round.

PLANNING IMPLICATIONS

Results of the long range energy systems forecasting confirm a widespread feeling that we have approached an era of new energetics, characterized by advanced nuclear technology, direct conversion processes, use of cryogenics in energy transportation and increased reliability of performance [Figure 1, Table 2]. Most important impending energy production break-throughs (within the next 15 years) include fuel cells for power generation at the sub-station level (1-10 MW), routine use of nuclear explosives in hydrocarbons extraction, large scale, low price coal gasification and liquefaction yielding high-B.T.U. 'pipeline' gas, widespread use of high temperature gas reactor (HTGR) coupled with closed cycle (Ackeret-Keller) gas turbine and liquid metal fast breeder reactor (LMFBR), the most critical component for the future of nuclear industry in the next few decades. Transportation innovations should bring extra high voltage (EHV) on very long distances and cryogenic transmission operating on the principle of superconductivity at very low temperatures.

There is a chance to have commercial magnetohydrodynamic (MHD) generation and cryogenic transmission of natural gas in the next decade, and there is a possibility of microwave transmission and another direct conversion method (thermionics) before the end of century. However, the most notable is an optimistic forecast of commercial availability of controlled thermonuclear power (fusion) before the year 2000, an opinion shared recently by an increasing number of knowledgeable scientists. Such a development would, of course, solve our 'energy crisis' once and for all, and many prospective conversion systems, which have been often portrayed as the future primary sources of our energy needs—e.g. solar bulk power devices, geothermal and tidal plants—could not compete with the fusion energy.

Environmental forecasts indicate an early appearance and perfection of safe, large scale disposal of long-lived radioactive wastes (salt dome projects), and routine commercial use of several environmental protection technologies which have been under an intensive development for some time [Figure 2, Table 3]. Virtually 'non-polluting' internal combustion engine (with emissions totaling less than 10 per cent of current exhausts), economical methods of stack gas de-sulphurization (yielding a marketable product, e.g. sulphuric acid or elementary sulphur) and effective and harmless control of accidental oil spills fall into this category. No new technologic break-throughs are needed to put water thermal pollution under control: it is rather a management problem to put several control techniques—dry cooling towers, total energy schemes (heating, cooling, sewage treatment with waste

TABLE 2. CONSENSUS ON ENERGY PRODUCTION, TRANSMISSION AND TRANSPORTATION: 50 PERCENT PROBABILITY ESTIMATES

Number	Item	Quartiles and Median
1.	Fuel cells for small scale power generation	1980-1980-1987
2.	Use of nuclear explosives in the production of natural gas and oil, geothermal heat etc.	1980-1980-1993
3.	Coal gasification or liquefaction	1979-1982-1984
4.	'Fail-safe' nuclear power generation	1976-1983-1995
5.	High temperature gas reactors (A-K cycle)	1979-1984-1990
6.	Extra high voltage transmission on very long distances (at least 1000 kV and 1000 km)	1979-1985-1990
7.	Fast breeder reactors	1981-1985-1990
8.	Cryogenic transmission systems using underground superconducting cables	1983-1985-1995
9.	Large scale shale oil recovery	1983-1986-1996
10.	Fossil fuel fired magnetohydrodynamics	1981-1988-1990
11.	Development of all practically feasible hydroelectric sites in populated regions	1982-1988-2000
12.	Techniques for economical recovery of additional 25 per cent of crude oil from known resources	1983-1988-1998
13.	Fully automated underground coal mining	1983-1988-2000
14.	Cryogenic pipeline transportation of natural gas	1986-1988-2000
15.	Simple solar furnace for home power generation in tropical and subtropical regions	1986-1990-2000
16.	Low cost high voltage underground transmission	1988-1990-2000
17.	Microwave power transmission	1990-1993-2000
18.	'Fail-safe' systems for drilling and producing hydrocarbons at any water depth	1987-1995-2002
19.	Direct conversion—thermionics	1985-1998-2010
20.	Utilization of low thermal difference systems	1990-1999-Never
21.	Controlled thermonuclear power	1990-2000-2000
22.	Efficient storage of electric energy in large quantities	1990-2000-2010
23.	Laser power transmission	1990-2000-2010
24.	Large and efficient tidal power plants	1992-2000-Never
25.	High temperature gas reactors with thermal cycle other than helium	2010-2010-2020 2010-2010-2020
26.	Widespread use of geothermal power	1990-2020-Later
27.	Relay of solar energy via satellite collectors	2000-2020-Later
28.	Solar energy devices for bulk power generation	2000-Later-Never
29.	Cryogenic superfluid transportation of mechanical energy on long distances	2020-Later-Never
30.	Utilization of gravitational energy (antigravity)	Later-Later-Never

heat)—and also some of the high efficiency conversion processes (e.g. Ackeret-Keller cycle) into a widespread usage. Delphi indicates that this might happen in the near future.

The main task of the Delphi study was to deal with the technological aspects of future energy production and environmental protection. But technological innovations without parallel social changes would be wholly insufficient to bring about the badly needed compromise between energy and the environment. That is why the Delphi inquired also into the future of several planning and management innovations and associated social changes. Among these, effective population control measures are essential. The Delphi forecast was optimistic, indicating that

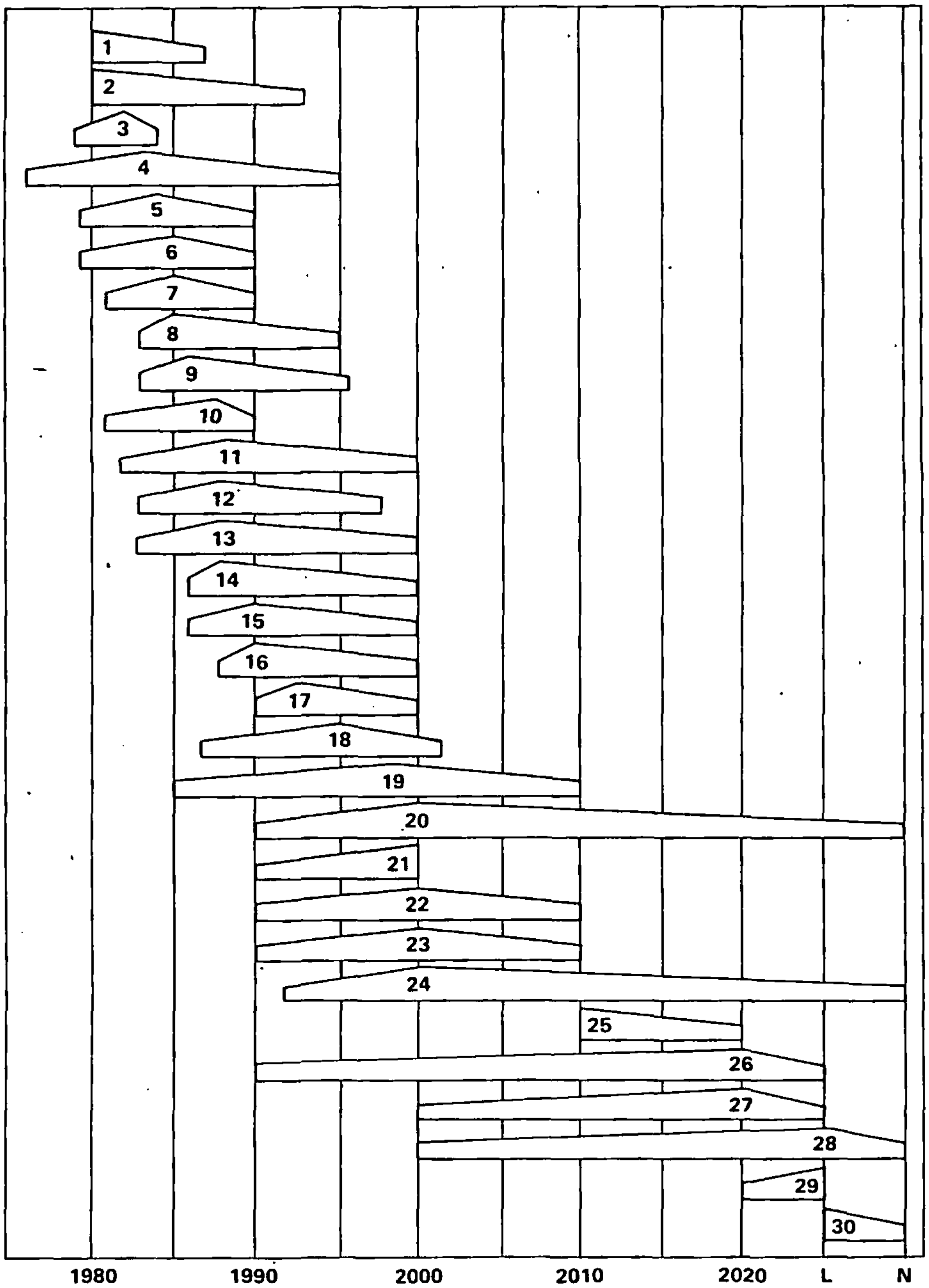

Figure 1. Consensus on energy production, transmission and transportation: 50 per cent probability estimates.

the 1990's might be the breakthrough decade in achieving stable population. Far less optimistic were the forecasts of future international cooperation: although there can be no doubt that the problems of energy supplies and environmental pollution are not bound by national boundaries, their solution or alleviation by a coordinated worldwide effort does not look too promising. We do not have worldwide air and water quality standards and we do not have a worldwide environmental surveillance and warning agency. Delphi did not offer any definite consensus as to

TABLE 3. CONSENSUS ON ENVIRONMENTAL PROTECTION, PLANNING AND MANAGEMENT: 50 PER CENT PROBABILITY ESTIMATES

Number	Item	Quartiles and Median
1.	Energy sources become the great pawn in international politics	1971-1971-1975
2.	Environmentally motivated higher price of energy	1973-1978-1983
3.	Acceptance of the idea that all consumers share responsibility for pollution and its cost	1975-1978-1980
4.	Safe, large scale disposal of radioactive wastes	1975-1980-1990
5.	'Non-polluting' internal combustion engine	1976-1980-1990
6.	Abolition of 'growth for growth's sake' concept	1977-1980-2000
7.	Practical, economical methods of stack gas desulphurization	1978-1980-1985
8.	Effective, harmless control of accidental oil spills	1978-1980-1985
9.	Dry cooling power plant towers	1976-1981-1986
10.	Development of waste heat utilization (desalting, heating, sewage treatment etc.)	1977-1983-1989
11.	Control of water thermal pollution	1977-1983-1987
12.	Nitrogen oxides control	1979-1983-1990
13.	New car-batteries, fuel cells, steam etc.	1980-1985-1992
14.	Offshore siting of large power plants	1981-1985-1997
15.	Removal of noxious matter from fossil fuels before combustion	1981-1986-2000
16.	Establishment of world wide environmental quality standards (air and water)	1985-1988-2000
17.	Taxes to alleviate pollution problems (effluent taxes, tax incentives for dispersal of people from large cities)	1983-1990-2000
18.	Establishment of world wide environmental surveillance and warning agency	1985-1990-2000
19.	Sound suppression of highways and airways	1986-1990-Later
20.	New fast and safe mass transit systems	1985-1992-2001
21.	Coordinated international planning of energy consumption	1986-1995-2020
22.	Application of Brayton power cycles to eliminate necessity of water cooling	1986-1995-Later
23.	Planned decrease of *per capita* energy demand and consumption	1988-2000-Never
24.	Effective population control	1990-2000-2000
25.	Conservation of fossil fuels for other future needs	1993-2005-Later
26.	Man will largely destroy his ability to survive in great numbers and in great cities	2000-2010-Later
27.	Utilization of heat sinks other than atmosphere and surface waters	1989-2020-Later
28.	Polar siting of large power plants	2005-Later-Later
29.	Application of new thermodynamic cycles (other than Brayton) to eliminate water cooling	2010-Later-Later
30.	Elimination of all fossil fuel fired generators	2016-Later-Later
31.	No private powered cars allowed	2017-Never-Never

when these important developments might happen.

Prospects of coordinated international planning of energy production and development are still worse—Delphi estimated the possible breakthrough for such action very inconclusively several decades from now. This caution is quite understandable in the time when almost two-

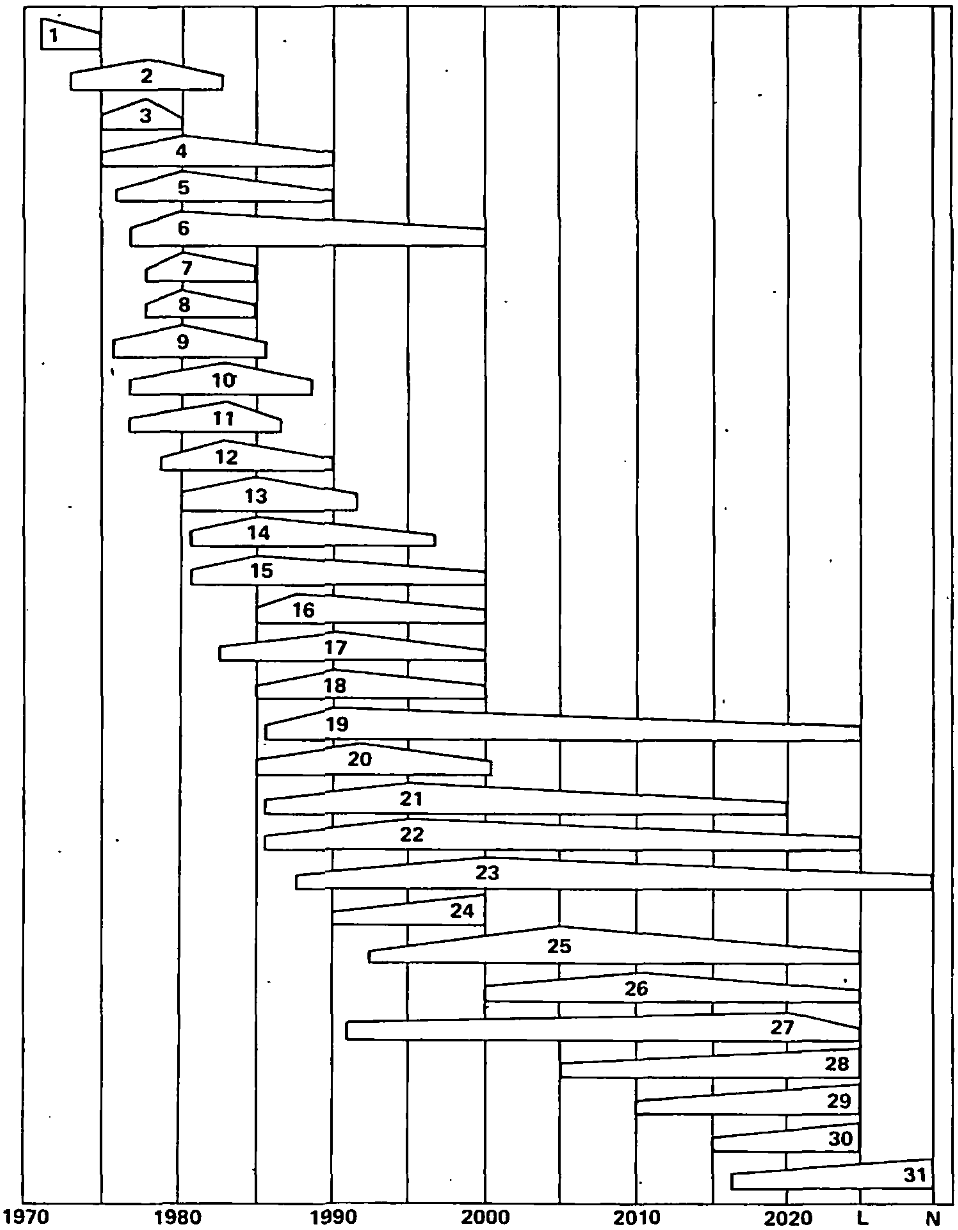

Figure 2. Consensus on environmental protection, planning and management: 50 per cent probability estimates.

thirds of Delphi respondents feel that energy resources have become the great pawn in international politics. A great many barriers in foreign relations will have to be dismantled and a new climate of mutual confidence established before some kind of coordinated international energy—environment policy, an essential need for mankind's survival, can be born.

The finiteness of the Earth, the necessity to control population, and a multitude of environmental considerations will also bring about a modification and later an inevitable rejection of the basic mechanism of modern societies—the persistent idea of continuing growth. This fact, as far as the energy industries are concerned, does not mean that we should start immediately to look for some social mechanism to discourage the growth of energy production and consumption *per se*. What we should be concerned with in the medium and long range is to substantially decrease and eventually halt the rate of growth. Delphi forecast such development as a gradual process over the next three decades.

Meanwhile, we must concentrate our resources, manpower, management and technological skill to work toward the solution of the most pressing energy–environment problems. Prior to this Delphi study, there was no consensus about which of the harmful effects of energy production is environmentally most important or most dangerous. The Delphi procedure established a ranked list of the priorities [. . . Table 4].

Air pollution is undoubtedly the leading problem: its various manifestations–car exhausts, gaseous (SO_2 and NO_X) and particulate emissions from fossil fuel combustion–occupy five among the first ten items on the list. Water pollution and water thermal pollution rank also very high, unlike radioactive wastes and emissions, which occupy only the tenth place. Certainly, it may come as a surprise that accidental oil spills or domestic heating are ranked higher. In fact, it is just an expression of fairly great confidence in the safe and reliable performance of nuclear power plants, an opinion well justified by their past record of safety and impending improvements in protective systems technology.

Two social problems on the list–irresponsibility of energy management and planning and the role played by conservationists–are worth mentioning. These two items occupied the eleventh and nineteenth place after the first round. After the second round the first item gained one rank, while the other gained three ranks. This higher ranking in both cases was predominantly a result of a unilateral and reciprocal action. Environmentalists ranked the irresponsibility of energy management higher in the second round and the majority of energy experts assigned greater importance to the actions of conservationists.

TABLE 4. CONSENSUS ON THE PRIORITIES OF ENERGY-ENVIRONMENT PROBLEMS

Rank	Item	Percentage Weight
1.	Internal combustion engine emissions	7.3
2.	Sulphur dioxide from power generation	6.9
3.	Particulate matter from combustion	6.4
4.	Water pollution by energy systems	5.9
5.	Thermal pollution by nuclear generation	5.9
6.	Nitrogen oxides from power generation	5.8
7.	Accidental oil spills	5.6
8.	Accumulation of waste	5.0
9.	Domestic heating (waste, air pollution)	4.9
10.	Radioactive wastes and emissions	4.8
11.	Thermal pollution by fossil generation	4.6
12.	Irresponsibility of energy management	4.6
13.	Coal mining environmental disturbances	4.4
14.	Carbon dioxide in upper atmosphere	3.5
15.	Visual pollution by overhead lines	3.0
16.	Concentration of pollution (economies of scale)	2.9
17.	Fossil fuels for combustion instead of chemical source	2.9
18.	Conservationists	2.7
19.	Export of modern technology to developing countries	2.6
20.	Miner's hazard	2.2
21.	Ecological and aesthetical impact of dams	2.1
22.	Carcinogenic effects of petroleum products	1.7
23.	Land use by power lines right-of-way	1.6
24.	Fog from wet cooling towers	1.3
25.	Earthquake danger to nuclear power plants	1.2

This little example shows clearly that the need for mutual understanding and reconciliation between the two leading parties in the energy–environment conflict cannot be overestimated. The two groups are still very much apart and this mutual wariness also surfaced in the Delphi study.

GROWTH LIMITS

Important conclusions for planning in various energy branches may be also drawn from the Delphi's evaluation of potential growth limits of 17 production and transportation technologies. During the postwar period the sizes, outputs and efficiencies of the energetics industry–be it petroleum tankers or power plant turbogenerators–have been increasing very rapidly. The current steep slopes of exponential curves must be put into broader perspective: for a great number of natural, technological and social reasons there must be upper limits for growth unless new methods and materials are discovered and adopted.

Table 5 shows some of the Delphi's estimates of growth limits in energy technologies.

When the growth of many traditional energy production and transportation systems is charted since their beginning in the last decades of the nineteenth century until their potential limits as estimated by the Delphi, it becomes clear that in the most cases the inflection points of the growth curves have been passed in the recent past or are about to be reached within the next decades. Typical growth S-curves are slowly forming, and the planning of energy facilities for the next decade will not have to rely on an unbounded growth which has characterized energy industries in the postwar period.

Among the critical considerations which will limit the future growth of many energy technologies is the dangerous impact of accidental environmental episodes. The catastrophe of a giant crude oil tanker of half million dwt [deadweight tons] would have a devastating impact on marine and beach ecology of a large area. Excessive concentration of combustion sources in a large urban region would dangerously aggravate the possibility of severe air pollution episodes, etc. Because similar episodes–'Torrey Canyon' wreck off the coast of England, New York Thanksgiving 1966 smog–attracted much attention in the last decade, the Delphi attempted to estimate their probability in the 1970's.

Severe urban air pollution episode lasting several days with significant consequences (excess mortality and morbidity) was assigned the highest probability–90 per cent. Widespread failure of power supply in populated, industrial region (similar to the famous Eastern U.S. 1965 blackout) and catastrophe of fully loaded jumbo tanker (over 100,000 dwt) are, according to the Delphi's consensus, also highly probable (70 per cent median chance). Serious oil spill from offshore drilling operations (characterized in the 1960's by the Santa Barbara 1969 incident) might be avoided in this decade (50 per cent probability) and the probability of radioactive

TABLE 5. GROWTH LIMITS OF THE TRADITIONAL TECHNOLOGIES

Technology	Unit	Median estimate of the growth limits
Largest turbogenerator in fossil fuelled power plant	MW	2000 in 1980
Total installed capacity of fossil fuelled power plant	MW	6000 in 1985
Voltage of long-distance transmission line	kV	1100 in 1980
Tonnage of crude oil tanker (in thousands)	dwt	500 in 1980
Diameter of long-distance crude oil pipeline	mm	1500 in 1985
Diameter of long-distance natural gas pipeline	mm	2500 in 1980
Tonnage of largest coal unit train (in thousands)	tons	30 in 1975

contamination of the environment outside of a reactor building, caused by a failure of nuclear power plant protective systems, is felt to be highly unlikely (median probability of such an accident was estimated only at 5 per cent).

Conclusions from the Delphi forecast *Energy and the Environment* can be divided into the two main categories. From the methodological viewpoint it was a confirmation that in spite of missing answers to many important questions about the mechanism and utility of the Delphi technique (What is expertise? What is a good consensus? How many iterations should be performed? What is the mechanism of opinion convergence?) we do know enough to perform and meaningfully evaluate even complicated and difficult Delphi exercises. Delphi proved to be a useful tool which may be relied upon in complex, intuitive inquiries. From the factual point of view, the Delphi's results offer a reason for qualified optimism. If our current and future technological potential will be used with responsible determination, and if certain important social changes will gradually become reality in the next two, three decades, then the chances for future compatibility of energy production and a clean and healthy environment are substantial.

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