ELSEVIER
Journal of Hazardous Materials 86 (2001) 55–75
Journal of Hazardous Materials
www.elsevier.com/locate/jhazmat

Science and precaution in the appraisal of electricity supply options

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Abstract

The technological risks associated with electricity generating options are a crucial consideration in the governance of energy strategies. Conversely, many central issues in the broader social debate over the governance of environmental risk (such as acid gas emissions, radioactive waste management, nuclear safety and global climate change) relate very strongly to technology choice in the electricity supply sector. The particularities of this field, therefore, offer a topical and pertinent case with which to explore the relationship between science and precaution in the governance of technological risk. By reference to the electricity sector, the present paper examines the contrasts between 'risk-based' and 'precautionary' approaches to the governance of risk, paying particular attention to the problems of intractable uncertainties and divergent values. A number of theoretical and methodological issues in conventional risk-assessment and cost–benefit analysis are examined and their practical implications for appraisal explored. Attention then turns to the form that might be taken by approaches to the governance of energy risks that are at the same time scientifically well-founded and precautionary. Conclusions are drawn for decision and policy making in this area.

Keywords: Electricity supply technologies; Sustainability; Precaution; Risk-assessment; Technology assessment

1. Introduction

Many central issues in the debate over the governance of environmental risk relate very strongly to the strategic choice of electricity supply options. Recent decades have seen the intensification of concerns over greenhouse gases, acid and particulate emissions, nuclear waste and accident risks and the ecological and landscape effects of large scale deployments of renewable energy technologies. The electricity sector, therefore, offers a topical and pertinent case with which to explore general issues in the governance of risk. Based on

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0304-3894/01/$ – see front matter
PII: S0304-3894(01)00255-2

various streams of research conducted over the past few years [1,2], this paper will focus on one particular theme in this wider debate: the active (and often polarised) debate over the relationships between science and precaution in the governance of technological risk.

A 'scientific' approach to the regulatory appraisal of risk is conventionally taken to imply the use of quantitative aggregating techniques such as comparative risk-assessment and environmental cost–benefit analysis. For reasons that will become clear later in this paper, these can be described as '*risk-based*' techniques. Such methods have been employed extensively in the electricity supply sector. They have been developed in this field to a state of elaboration and maturity matched in few other fields. Indeed, so intense has been the activity, that regulatory appraisal in this area might in many ways be taken as the paradigm application of such methods in the governance of technological risk. The basic aspiration underlying the use of 'risk-based' techniques is that in and of themselves, they offer a robust means to prescribe and justify commercial and regulatory decision-making in the governance of technological risk. The authority of this 'risk-based' approach lies in an appeal to monolithic notions of methodological rigour and on the unitary nature of the analytical results thereby obtained.

For its part, a '*precautionary*' approach reflects a rather different perspective, introducing a wide range of emerging concerns in the risk governance debate. In the most general of terms, it contrasts with a reductive 'risk-based' approach in extending attention to themes, such as complexity, variability and nonlinear vulnerabilities in natural systems. A precautionary approach highlights the consequent potential for 'surprise'. It places greater emphasis on active and dynamic choices between technology and policy alternatives than do 'risk-based' approaches and makes a point of focusing on the interests of those who stand to be affected, rather than those of the proponents of a particular technology or investment. The general attitudes embodied in a 'precautionary approach' might be characterised as inclusivity and pluralism in the appraisal of risks and benefits, humility in the face of uncertainty and the adoption of more deliberately holistic and long-term perspectives. These are often influenced by a 'biocentric ethic' under which the well-being of living things is ascribed a value in its own right, rather than in terms of any utility to humans [3]. In this way, a 'precautionary approach' introduces an apparently formidable array of additional issues to the conventional 'risk-based' governance of risk.

This series of rather diffuse socio-political themes has been given more concrete formal expression in the shape of the precautionary principle. As an emerging principle of law, this has become embodied in an ever-increasing number of national and international statutory instruments over recent years [4]. To cite a particularly influential formulation, Principle 15 of the 1992 Rio Declaration holds the precautionary principle to require that "*Where there are threats of serious or irreversible damage, lack of full scientific certainty shall not be used as a reason for postponing cost-effective measures to prevent environmental degradation*". Although more narrowly-framed than the wider array of issues informing the precautionary approach, key aspects of the precautionary principle still remain ambiguous. For instance, questions may be raised over the precise interpretation of concepts such as 'threat', 'irreversibility', 'full scientific certainty' and 'cost-effectiveness' in the typical formulation given here. As a result, discussions over the implications of any particular formulation of the precautionary principle tend typically very quickly to invoke the full range of wider issues associated with the general debate on the 'precautionary approach'.

One key implication of the precautionary principle and a feature of the associated broad 'precautionary approach' is a reduced reliance on quantitative appraisal techniques like risk-assessment and cost–benefit analysis and a greater emphasis on more open-ended, qualitative, participatory deliberation in the governance of risk [5]. This has been taken in many areas as a sign of a tension or even contradiction between the characteristics of 'precautionary' policy and the disciplines associated with 'scientific' approaches to regulatory appraisal. Indeed, the view has been expressed in some quarters that a 'precautionary approach' is so lacking in its theoretical framework and so ambiguous in its practical implications, that it is of little or no value in the governance of risk. At the extreme, it is feared, pursuit of 'precaution' would militate against the adoption of any new technology at all and so represents a retreat from deeply held convictions over the positive potential of technological progress.

There is no doubt that there do exist important differences of emphasis between different formulations of the precautionary principle and of the broader 'precautionary approach' to the governance of risk. Partly for this reason, the implications for policy making in any particular area (such as the electricity sector) remain ambiguous and contested. However, what is less well-recognised is that orthodox 'risk-based' approaches (such as risk and cost–benefit analysis) also display serious inconsistencies and present fundamental difficulties for the practical business of decision-making. By reference to an extensive literature concerned with the appraisal of electricity supply technologies, this paper will first examine the nature and scale of these practical and theoretical problems. It will then outline a general conceptual model for thinking about the relationship between 'science' and 'precaution' in the regulatory appraisal of technological options. Finally, a number of conclusions will be drawn concerning the way in which the governance of technological risks, for instance in the electricity supply industry, might at the same time become more scientifically well-founded and more precautionary in character.

2. Key methodological issues

From the late 1970s to the early 1980s, the dominant analytical approach to the regulatory appraisal of electricity supply options worldwide was provided by comparative risk-assessment. From the late 1980s to the mid 1990s, the techniques of environmental cost–benefit analysis (or 'environmental valuation') had at least in the industrialised market economies, begun to complement and, increasingly, substitute the role played by risk-assessment. Over this whole period, there accumulated an increasingly substantive body of criticism of both approaches. [1] Serious questions were raised concerning the degree to which the aggregated numerical indices derived in risk and cost–benefit analysis might satisfactorily reflect the scope, complexity, disparity and subjectivity of different aspects of the environmental performance of energy technologies. The following section summarises some of the key themes in this debate over the use of such 'risk-based' approaches in regulatory appraisal of electricity supply options.

[1] For instance, specifically with regard to energy technologies, see [6–14].

The impacts associated with different generating technologies may differ radically in the *forms* which they take. For instance, some may be more manifest as risks of death, others as injury or disease. They may differ in the immediacy or latency of their impacts. The effects of some options may be concentrated in a few large events, whereas others may spread across a larger number of smaller incidents. Effects of different options may vary in the degree to which they are reversible. The determination of the relative importance of these different dimensions must inevitably be a highly circumstantial and subjective matter. The aggregated numerical values obtained in 'risk-based' analysis compress these different dimensions onto a single yardstick, adopting implicit assumptions about their relative importance.

The impacts caused by different energy options also differ in terms of their *distribution* across space, through society and beyond. This raises issues concerning the 'fairness' of the distribution of impacts across different groups and the way this correlates (or not) with the distribution of the benefits arising from the operation of the investments concerned. Particularly intractable difficulties emerge in contemplating the distribution of risks through time, and the balance between burdens which fall on human and non-human life. Where the patterns in the distribution of the risks of different energy options vary along these dimensions, further serious questions must be raised about the value of discrete numerical results, such as those delivered by risk and cost–benefit analysis.

The risks of different electricity supply options also impact differently on the *autonomy* of those affected. Exposure to the effects of some technologies is more voluntary than is the case for others. Likewise, different effects vary in their familiarity and the degree to which they are controllable. Further serious, complex and pervasive issues are raised in considering the trust that should be placed in the communities and institutions associated with the operation of the different options, and the appraisal results which they obtain.

Turning to the characteristics of analysis, rather than the risks themselves, the results obtained in environmental appraisal are, obviously, highly sensitive to the selection of primary quantitative *indicators*. Although final results are (in cost–benefit analysis) expressed as monetary values or (in risk-assessment) mortality or morbidity frequencies, these represent conversions and aggregations over a wide variety of basic indices. The different primary metrics employed with each individual risk may vary radically in the degree to which they capture the full character of that individual effect and the fidelity with which they track its dynamics. Some effects are intrinsically much more readily quantifiable than others, compounding the potential for incoherence between the approaches adopted to different effects both within individual studies, and between different studies.

A further issue is raised in the choice of particular appraisal *methodologies*. In short, different studies tend to emphasize different methods. Some cost–benefit studies obtain their results largely through the pursuit of a 'mitigation cost' approach, based on an assessment of the costs incurred in alleviating environmental damage once committed (e.g. [15]). Other studies mix results obtained through application of mitigation cost techniques (e.g. to certain atmospheric effects) with values obtained by the use of 'hedonic market' and 'contingent valuation' methods (e.g. to certain water effects) which assess values, respectively, by examining prevailing property or wage markets or responses to questionnaires (e.g. [16]). Still other analysts favour the use of 'abatement cost' techniques, which take the costs of controlling pollution at source as a proxy indicator for the social costs of the environmental impacts thereby avoided (e.g. [17]). A final group of studies, is based mainly on a fourth methodology: the 'damage function' technique (e.g. [18]). This involves the 'bottom-up' assessment of the costs associated with each physical dose–response relationship. There is a considerable literature concerning the relative merits and deficiencies of these different techniques (e.g. [19–21]). The differing characters of these approaches and the fact that the results obtained for specific effects are found often to vary significantly between methods, are suggestive of important difficulties of resolution, fidelity and coherence in 'risk-based' analysis.

One of the most important issues in the general field of regulatory appraisal concerns the response to *uncertainty*. In studies of individual classes of risk or environmental effect, it is typical that upper and lower bounds to the ranges of results expressed in individual studies may differ by several orders of magnitude (e.g. [22–25]). Against this background, it might be thought reasonable that many risk-assessment studies express their numerical results only to one (e.g. [23,26]) or two (e.g. [24,27]) significant figures. It is curious, then, that-over the years, a significant number of energy risk studies evidently feel such confidence in their results that they employ as many as three significant figures (e.g. [8,22,25,28,29]).

The treatment of uncertainty in the energy cost–benefit literature is even more optimistic. Despite the inherent intractability of their task, authors of energy externality studies often seem to feel they can justify levels of precision which are at least as great, and sometimes greater, than any professed elsewhere in the environmental appraisal literature. For instance, a 1990 study for the US Department of Energy [16] and a report for the German electricity industry in 1989 [30] give some results to three significant figures. A pioneering study by Hohmeyer for the European Commission in 1988 presents results to a daunting four significant figures [15,31]. Likewise, the stated ranges of variation of valuation studies are similarly indicative of higher confidence than that enjoyed by other approaches to environmental assessment. Hohmeyer's ranges are as narrow as factor 10 at the most [15,31,32], whilst Ottinger et al. [16] and a study for the UK Department and Industry [33] present no ranges at all in some final results. The 1995, Externe study for the European Commission adopts a more sophisticated approach to the treatment of data quality, specifying the degree of confidence associated with the values obtained for different disaggregated effects and itself avoiding summing over categories [18]. However, even this study nevertheless presents its results as discrete values rather than as ranges or sensitivities. Where qualifications are buried in the more theoretical passages of such studies, they are all too easily lost in derivative work which treats the results obtained as if they were meaningfully additive (e.g. [34]). Some of the key aspects of uncertainty which are concealed in this ostensibly precise mode of presentation are returned to in the next section.

The sixth and final set of difficulties in the conventional 'risk-based' appraisal of electricity options concerns the fundamental underlying assumptions adopted in the *framing and presentation* of the analysis. In short, assumptions concerning the specific operational circumstances of the different options, their developmental trajectories and the 'system boundaries' set for the purpose of analysis may all have a determining influence on the nature of the results obtained. Further issues may be raised in considering the degree to which any individual set of results constitute a 'complete' account of the issues pertaining to any individual decision, and the way in which those factors which are included in analysis are articulated with those which are not in subsequent interpretation of results.

To illustrate the potential importance of these 'dimensions of variability' in determining the results of 'risk-based' analysis, examples may be given concerning just two such factors in recent cost–benefit studies of electricity options: the treatment of system boundaries, and the completeness in the scope of analysis. The apparently neat numerical values derived in 'risk-based' analysis may conceal the crucial fact that different studies address different stages in the 'fuel cycles' associated with individual options and in the 'life cycles' of associated facilities. Hohmeyer's 1988 study (and its subsequent updates) are essentially restricted to the electricity generation stage (omitting mining or drilling, fuel processing, storage and transport and waste management) and to the operational phase (omitting inputs of energy and materials, and the impacts of the construction and decommissioning processes) [15]. The 1990 Ottinger et al., study is almost as restricted in scope, addressing waste management burdens and decommissioning (for some options but not others) [16]. The 1992 study for the UK DTI adopts wider system boundaries, including some reference to fuel extraction, processing, transport and storage and waste management, but also omits material and energy inputs and construction and decommissioning impacts [33]. With the exception of the 1995 Externe report [18], it is notable that the system boundaries set in valuation studies tend to be much narrower than those which have for some time been conventional in the comparative risk-assessment of energy options (e.g. [23,26,27,29,35]). Even the Externe report [18], however, omits energy and material inputs to construction of fossil and nuclear facilities, while including these for some other options. Crucial underlying assumptions on system boundaries are not conveyed in aggregated numerical results. As a result, 'risk-based' assessments are vulnerable to serious difficulties of interpretation.

A similar picture emerges with respect to the completeness of risk-based methods. Different studies include and exclude different categories of effect. Hohmeyer's 1988 cost–benefit study for the European Commission [15] (and its subsequent revisions [31,32]) exclude aesthetic effects, thereby omitting a factor widely regarded as the most serious single environmental impact of wind power. The 1990 Ottinger et al., study [16] does address aesthetic impacts, but omits to account for occupational safety risks, another potentially important effect in assessing wind power. Although relatively comprehensive in scope, the major 1995 Externe study [18], also conducted for the European Commission, excludes global warming from its final numerical results, despite the fact that this is addressed in both the other earlier studies mentioned. The Externe study also omits to address the possibility of environmental damage due to terrorist attacks or sabotage at nuclear power stations, factors which are elsewhere often viewed as significant [36]. All three studies exclude any attention to the environmental implications of nuclear proliferation, although efforts in this regard are made elsewhere (e.g. [14,37]). Despite including some of the most thorough and systematic studies in the field, each of these reports, in different ways, may, therefore, be judged to be seriously incomplete. If risk-assessment or cost–benefit results are taken at face value, then this important factor is entirely missed.

When these various issues are taken together, it is an uncomfortable but undeniable fact that the adoption of different but equally reasonable assumptions or conventions on potentially any one of the different dimensions of appraisal may radically affect the results of 'risk-based' analysis of the impacts of different electricity generating options. Yet these crucial assumptions are exogenous to the 'scientific' analysis and essentially contingent and subjective in nature. The more recent cost–benefit approaches seem no more able to avoid this problem than did comparative risk-assessment before them. Indeed, based on the examples provided here, it may be difficult to escape the conclusion that by combining additional methodological complexity with apparent presentational simplicity, the more elaborate methods of cost-analysis can make the problem worse rather than better. In short, the notion that orthodox 'scientific' approaches to regulatory appraisal necessarily yield a clear, robust and pragmatic basis for the governance of energy risks seems seriously flawed.

3. Underlying theoretical problems

To some, this discussion of variability and inconsistency in the subjective assumptions underlying apparently scientific 'risk-based' approaches to appraisal may seem rather superficial, simply indicating a circumstantial lack of firm methodological disciplines and conventions. Would it not be possible to solve the difficulties presented for risk governance simply by standardising the methods and procedures of regulatory appraisal? Unfortunately, reference to the theoretical literature shows that the problems are far more deep-seated and intractable than this. Indeed, these difficulties may be taken to reflect the most basic principles in the 'scientific' foundations of probability and rational choice theory: 'incommensurability' (comparing "apples and oranges") and 'ignorance' ("we do not know what we do not know").

Both issues follow naturally from the discussion in Section 2. Assuming for a moment that the regulatory appraisal literature displayed a level of consistency and completeness far beyond that which is typically achieved, then there would still be the question of how the different aspects of energy risks are to be framed and prioritised in appraisal. For instance, to what extent should analysis be based on well-documented past empirical data relating to possibly outdated options, superseded practices or irrelevant circumstances or to what extent should it make use of theoretical models of performance based on extrapolations, projections and untested assumptions? How should individual unquantifiable aspects of risk be taken into account? Even where they are fully quantifiable, there is the question of the relative priority that should be attached to the different factors in the aggregation of effects, such as toxicity, carcinogenicity, allergenicity, occupational safety, biodiversity or ecological integrity? What relative weight should properly be placed on impacts to different groups, such as workers, children, pregnant and breastfeeding mothers, future generations, disadvantaged communities, foreigners, those who do not benefit from the technology in question or even to animals and plants as beings in their own right?

Even if they were practically feasible, objectives such as completeness or comprehensiveness do not assist in addressing issues of framing and prioritisation of this kind. No one set of assumptions or priorities may be claimed to be uniquely rational, complete or comprehensive. It is this which constitutes the problem of incommensurability, a classic and well-explored dilemma in the field of social choice, but one that is frequently forgotten in regulatory appraisal. For, it is a fundamental consequence of the underlying axioms of utilitarian rationality that neither risk-assessment and cost–benefit analysis have developed a definitive way of resolving the difficulties in comparing apples and oranges. Even the most optimistic of proponents of rational choice acknowledge that there is no effective way to compare the intensities of preferences displayed by different individuals or groups in society. Indeed, even where social choices are addressed simply in ordinal terms, the economist Kenneth Arrow went a long way towards earning his Nobel Prize for demonstrating formally from first principles within the rational choice paradigm that it is *impossible* definitively to combine relative preference orderings in a plural society [38].

Put simply, the point is that “it takes all sorts to make a world”. Different cultural groups, political constituencies or economic interests typically attach different degrees of importance to the different aspects of technological risk and look at them differently. Within the bounds defined by the domain of plural social discourse, no one set of values or framings can definitively be ruled more ‘rational’ or ‘well informed’ than many others. Even were there to be complete certainty in the quantification of all the various classes and dimensions of risk, it is entirely reasonable that fundamentally different conclusions over environmental risk might be drawn under different, but equally legitimate, perspectives. It is a matter of the science of social appraisal itself, then, that there can be no ‘analytical fix’ for the problems posed by complexity and subjectivity in the governance of risk. It is ironic that the application of ‘scientific’ techniques such as risk and cost–benefit analysis should so often neglect such a fundamental result arising from their own underlying scientific first principles.

The second fundamental problem underlying the social appraisal of technological risks concerns incomplete information. It is a central feature of ‘risk-based’ approaches to regulatory appraisal that incompleteness in empirical and theoretical knowledge is addressed by applying quantitative probabilistic methods. Indeed, in economics and utility theory, this is the essence of the well-established formal definition of *risk* itself. Here ‘risk’ is, by definition, a condition under which it is possible both to define a comprehensive set of all possible outcomes *and* to resolve a discrete set of probabilities (or a density function) across this array of possibilities. This is illustrated in the top left hand corner of Fig. 1. It is a domain under which the various techniques of risk-assessment are applicable, permitting (in theory) the full characterisation and ordering of the different options under appraisal. There are a host of details relating to this picture (such as those hinging on the distinction between ‘frequentist’ and ‘Bayesian’ understandings of probability), but none of these alter the fundamental definition of the concept of risk.

The strict sense of the term *uncertainty*, by contrast, applies to a condition under which there is confidence in the completeness of the defined set of outcomes, but where there is acknowledged to exist no valid theoretical or empirical basis confidently to assign probabilities to these outcomes. This is found in the lower left hand corner of Fig. 1. Here, the analytical armoury is less well-developed, with the various sorts of sensitivity and scenario analysis being the best that can usually be managed [39]. Whilst the different options under appraisal may still be broadly characterised, they cannot be ranked even in ordinal terms without some knowledge of the relative likelihoods of the different outcomes.

Both risk and uncertainty, in the strict senses of the terms, require that the different possible outcomes be clearly characterisable or subject to measurement. The discussion in Section 2 has already made it clear that this is often not the case, the complexity and scope of the different forms of environmental risk and the different ways of framing and prioritising these, can all, too-easily render *ambiguous* the definitive characterisation of outcomes (top right corner of Fig. 1). Where these problems are combined with the difficulties in applying the concept of probability, we face a condition which is formally defined as *ignorance*

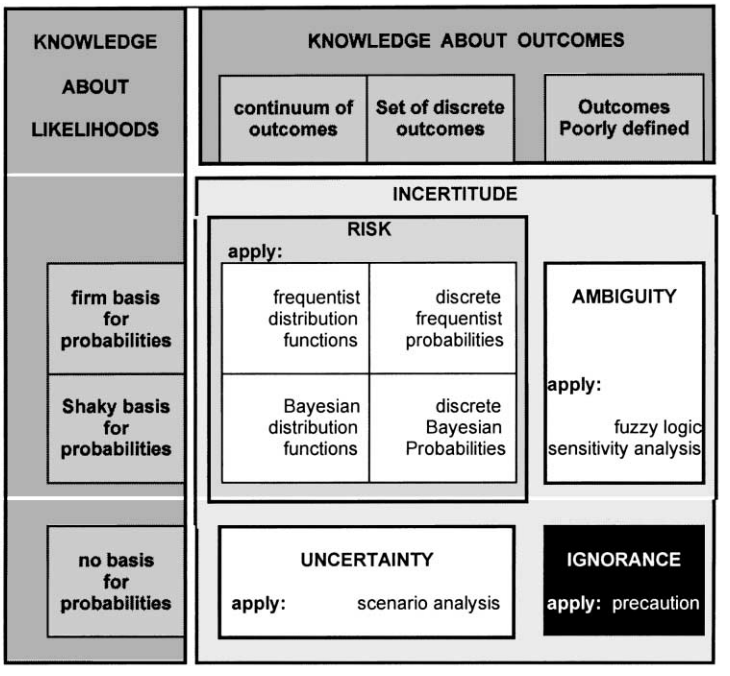

Fig. 1. The formal definitions of risk, uncertainty, ambiguity and ignorance.

(bottom right corner of Fig. 1) [40–42]. This applies in circumstances where there not only exists no basis for the assigning of probabilities (as under uncertainty), but where the definition of a complete set of outcomes is also problematic. In short, recognition of the condition of ignorance is an acknowledgement of the possibility of surprise. Under such circumstances, not only is it impossible definitively to rank the different options, but even their full characterisation is difficult. Under a state of ignorance (in this strict sense), it is always possible that there are effects (outcomes) which have been entirely excluded from consideration.

Fig. 1 provides a schematic illustration of the relationships between these formal definitions for the concepts of risk, uncertainty, ambiguity and ignorance. It is quite normal, even in specialist discussion, for the full breadth and depth of these issues to be conflated in the simple concepts of 'risk' or 'uncertainty', thus, seriously understating the difficulties involved. In order to avoid confusion between the strict definitions of the terms risk and uncertainty as used here, and the looser colloquial usages, the term 'incertitude' can be used in a broad overarching sense to subsume all four subordinate conditions.

It is not difficult to see that it is the formal concepts of ignorance and strict uncertainty (rather than risk) which best describe the salient features of risk governance. Some of the main technologically-induced 'risks' of our time (such as stratospheric ozone depletion, endocrine disrupting chemicals and BSE) are all cases where the problem lay not so much in the determination of likelihoods, but in the anticipation of the very possibilities themselves.

They were effectively surprises. In the energy sector, imponderables such as those associated with global climate change, geological diffusion models for high level radioactive waste repositories and even the long-term effects of major dependencies on renewables like biomass are all as much matters of ignorance and uncertainty as they are of risk in the strict sense. Even where there is some confidence over the broad likelihood of an overall phenomenon like global climate change, there are still crucial questions over the implications for any specific region or human activity [43], invoking the formal condition of 'ambiguity' in the top right corner of Fig. 1.

The curious thing is that these and other sources of intractable uncertainty and ignorance are routinely treated in the regulatory appraisal of technology by using the probabilistic techniques of risk-assessment. Given the manifest inapplicability of probabilistic techniques under conditions of uncertainty and ignorance, this is a serious and remarkable error. For all the seductive elegance and facility of probabilistic calculus, it remains the case that judgements concerning the extent to which "we do not know what we do not know", no matter how well informed, are ultimately and unavoidably qualitative and subjective. The treatment of uncertainty and ignorance as if they were mere risk effectively amounts to what the economist Hayek dubbed (in his Nobel acceptance speech) the "pretence at knowledge" [44]. Far from displaying a respect for science in regulatory appraisal, the effect of such scientistic oversimplification is actually to ignore and undermine scientific principles.

Both with respect to 'incommensurability' and 'ignorance', then, it is clear that the aspiration to definitive prescriptive conclusions through 'risk-based' approaches to regulatory appraisal is not only hitherto unachieved in the governance of energy technologies. Nor is it just unfeasible in practice. In a plural society, a unitary 'sound scientific' basis for the governance of technological risk is a fundamental contradiction in terms!

4. Practical consequences

The theoretical and methodological issues discussed in Sections 5 and 6 are borne out by examination of the practical results obtained in the risk and cost–benefit literature over recent years. Based on a survey of influential government and industry-sponsored studies conducted in industrialised countries [13], Fig. 2 displays the degree of variability evident in the literature as a whole in relation to just one option — modern coal power. [2] The highest and lowest externality values for this technology vary by more than four orders of magnitude, far exceeding the range expressed in any individual study. There is no clear trend evident over time, nor even a consistent relationship between the results of those studies which include and exclude global warming.

When attention turns to a comparison of the externality results obtained for a range of *different* electricity supply options, the ambiguity of the overall picture is further compounded. Based on the same survey [13], Fig. 3 displays the externality values derived in the literature as a whole for eight key generating options. Again, the picture is dominated by enormous variability. Individual studies show results at the high end of the overall range for some options but lower in the distributions for others. Indeed, since the lowest

[2] References are given in full in Stirling [13].

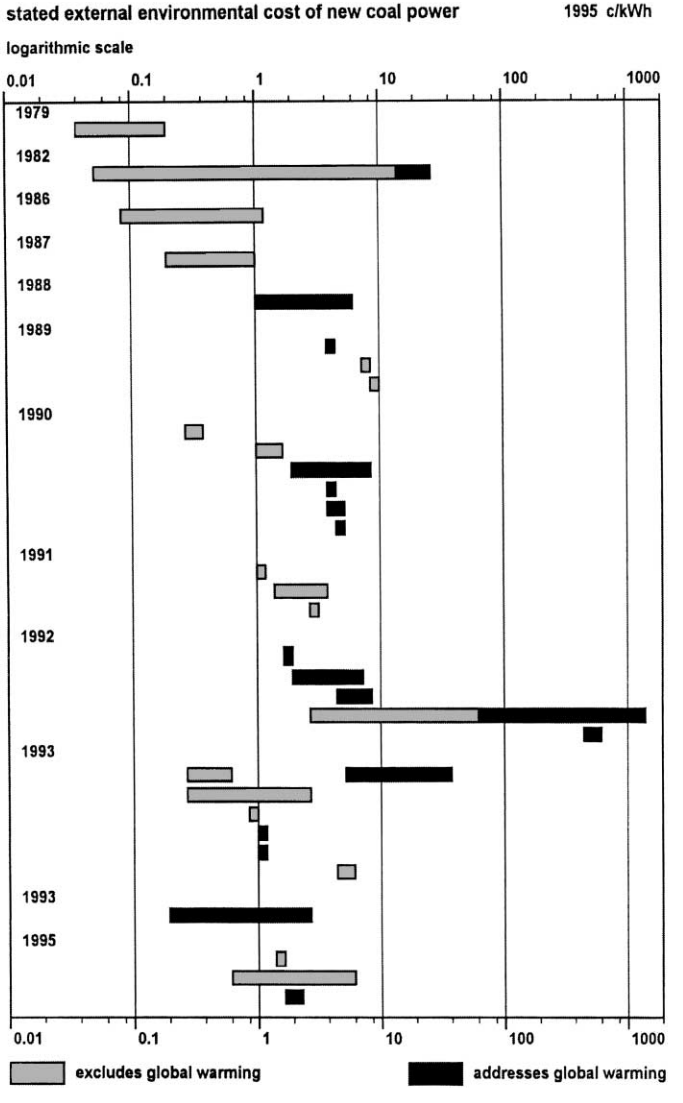

Fig. 2. Variability in the regulatory appraisal of energy options (the case of coal power).

values obtained for the generally worst-ranking option (coal) are lower than the highest values obtained for the apparently best ranking options (wind), the overall picture would accommodate any conceivable ranking order for these eight options.

It is evident from the variability of results displayed in Figs. 2 and 3 that the wide range of exogenous assumptions required in 'risk-based' appraisal can have an enormous impact on the practical results. Since a variety of different 'framing assumptions' may all be equally 'rational', there is little prior reason to regard as 'definitive', the results obtained under any

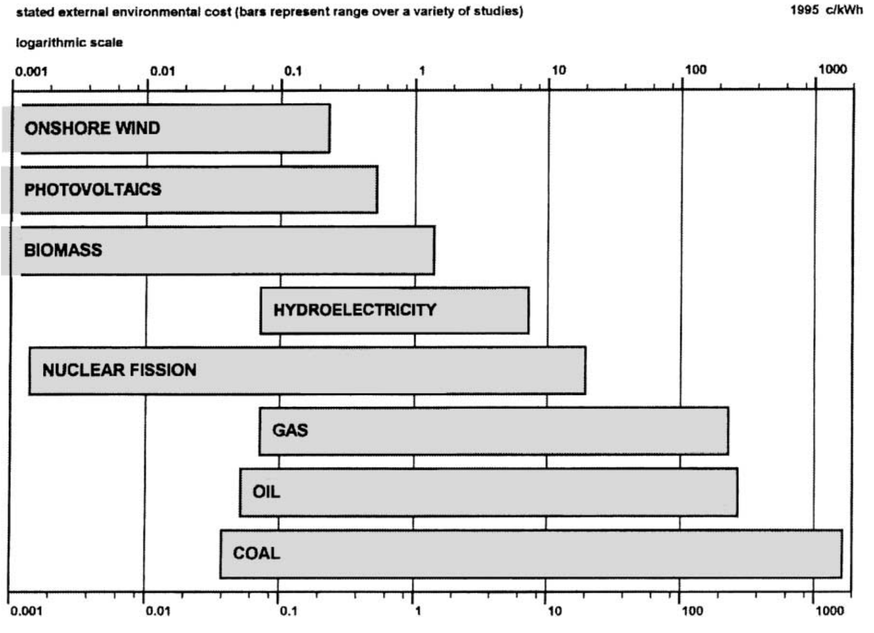

Fig. 3. Ambiguity in the regulatory appraisal of electricity supply options.

one individual set of assumptions. Consequently, it is apparent from the ambiguity of the picture in Fig. 3 that the regulatory appraisal literature taken as a whole fails to provide an unequivocal basis even for the *ordinal* ranking of electricity supply options. One of the most basic initial tasks in the governance of risk is to achieve some notion of the overall ordering of different options under different assumptions. Since many of the dimensions of variability discussed in this section typically remain implicit in much risk-assessment and cost–benefit analysis, serious questions arise over whether, taken at face value, the results of such ‘risk-based’ methodologies are of much practical policy use at all.

5. Science and precaution in the governance of risk

It is with increasing realisation of these practical and theoretical limitations to the value of ‘risk-based’ approaches to the governance of technological risk, that interest is growing in complementary and alternative approaches. In particular, as discussed in Section 1, a ‘precautionary approach’ is becoming an ever more prominent feature of the regulatory debate on environmental risks, with the precautionary principle featuring increasingly in national and international legislation [4,5,45]. Although subject to a variety of different definitions, in the broadest of terms, a ‘precautionary’ approach responds to the difficulties in risk-assessment documented here by granting greater benefit of the doubt to the environment and to public health than to the activities which may be held to threaten these things. A host of different practical instruments and measures are variously proposed in different contexts as embodiments of a ‘precautionary approach’ or as means to implement a ‘precautionary principle’. These are reviewed elsewhere (e.g. [3,45]). For present purposes, attention will concentrate on the way in which a precautionary approach offers a direct response to the practical and theoretical problems of regulatory appraisal which have been discussed in this paper so far.

One key theme in the current lively debate on these matters surrounds the frequent assertion (and sometimes assumption) that whatever form it takes, a ‘precautionary’ approach to the management of environmental risk is somehow in tension with (or even antithetical to) the generally uncontroversial aspiration that regulatory decision-making should be based on ‘sound science’. Of course, as noted, this does not address the extent to which orthodox ‘scientific’ approaches such as comparative risk-assessment are actually consistent with scientific principles of rational choice, or may themselves be claimed to yield ‘sound’ results. The thrust of the discussion, thus, far has been to raise serious doubts over this. Nevertheless, the important question remains as to what exactly is the relationship between so-called ‘scientific’ and ‘precautionary’ approaches in the governance of technological risk?

In answering this question, a necessary starting point would be a clear characterisation of exactly what is meant by ‘science’ and ‘precaution’. Drawing on a wide literature, Stirling [2] discusses a series of idealised attributes of ‘scientific’ approaches to regulatory appraisal. In short, a scientific approach to the governance of technological risk should, ideally and at minimum, be *transparent* in its argumentation, *systematic* in its analytical methods, *sceptical* in its treatment of knowledge claims, subject to *peer review*, *independent* from special interests, professionally and democratically *accountable* and continually open to *learning* in the face of new knowledge.

Likewise, drawing on an equally extensive parallel literature (reviewed in [3]), it is possible broadly to characterise the essential features of a ‘precautionary’ approach to the governance of technological risk. A ‘precautionary approach’ involves the application of subordinate principles that ‘*prevention is better than cure*’, that ‘*the polluter should pay*’, that options offering simultaneously better economic and environmental performance should always be preferred (‘*no regrets*’), that options should be appraised at the level of *production systems* taken as a whole and that attention should be extended to the intrinsic value of *non-human life* in its own right. In effect, this is variously taken to mean a certain *humility* about scientific knowledge, a recognition of the *vulnerability* of the natural environment, the prioritising of the *rights* of those who stand to be adversely affected by environmental risks, always taking account of available *alternatives*, continued acknowledgement of the *complexity* and *variability* of the real world, and the adoption of *long-term*, *holistic* and *inclusive* perspectives in the governance of technological risks.

In many ways, these attributes of a ‘precautionary approach’ can be seen to concern different aspects of the *breadth* of the regulatory appraisal process. A ‘broad’ regime is one that takes account of a wide range of different types of impact, including qualitative as well as quantitative issues and including indirect as well as direct effects. Likewise, a ‘broad’ framework accommodates a diverse array of different points of view (including, importantly, those of potential ‘victims’) and anticipates a wide range of possibilities in the face of uncertainty and ignorance. It extends consideration to the benefits and justifications associated with the introduction of the technology in question and examines a variety of alternative ways in which the benefits of a regulated technology might be realised at lower

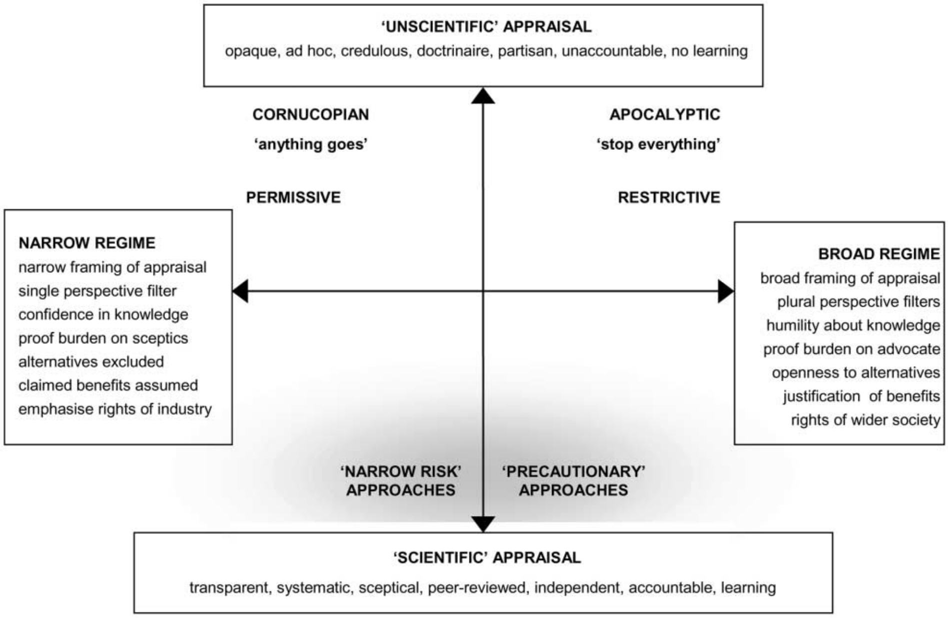

Fig. 4. A model of the relationships between the concepts of risk, science and precaution.

levels of risk. Taken together, these features constitute a more 'precautionary' approach because they increase the number and intensity of the constraints that any technological option must satisfy in order to be approved by the regulatory process, thus, making the governance regime more demanding. At the same time, however, such measures might equally serve to encourage alternative technological innovations that might otherwise remain neglected.

What is interesting about this characterisation of 'precaution' in terms of the 'breadth' of the associated regulatory appraisal regime, is that it reveals an inherently consistent, and in many respects complementary, relationship between 'precaution' and 'science' in the governance of technological risk. Fig. 4 distinguishes between different approaches to risk management based on the degree to which each embodies the respective characteristics of 'scientific appraisal' and 'breadth of framing' identified here. Of course, both the 'broad'/'narrow' and the 'scientific'/'unscientific' dichotomies drawn here are highly stylised and simplified. However, the broad picture revealed in Fig. 4 is at least richer and more realistic than any one-dimensional dichotomy between 'science' and 'precaution'. Taken together, the combination of these two dichotomies generates the four-fold array of idealised permutations displayed in Fig. 4. The adoption of a 'narrow' regime without reference to scientific understandings or disciplines in appraisal might be described as a *permissive* position. Taken to an extreme, this would amount to an entirely uncritical 'anything goes' approach to the governance of technology of the kind associated with caricature 'cornucopian' visions of progress. Similarly, a broad-based regime might be similarly unscientific. The resulting *restrictive* position might be associated with a caricature 'apocalyptic' vision of progress. In the extreme, it would lead to a situation of paralysis under which no new technological innovation that offends in the slightest respect would ever be deployed. The crucial point is that neither the ‘permissive’ (cornucopian) nor the ‘restrictive’ (apocalyptic) positions as defined here would be subject to challenge or reversal by the disciplines of scientific discourse associated with the vertical axis.

It is clear that neither the established procedures of risk regulation (based on relatively narrowly-framed risk-assessment methods) nor the emerging precautionary approach (based on broader perspectives and considerations) actually resemble these stylised ‘permissive’ or ‘restrictive’ caricatures. Existing risk-assessment-based regulation includes a host of effective checks and balances. It certainly does not necessarily provide for the uncritical approval of any new technology that may be developed. Likewise, even the most progressive formulations of a ‘precautionary principle’ are circumscribed in their scope, admit an incremental series of instruments and allow for regulatory approval under a host of favourable conditions. Both approaches are compatible, at least in principle, with the requirements of systematic methodology, scepticism, transparency, quality control by peer-review, professional independence, accountability, and an emphasis on learning which are held here for the purposes of discussion to be among the key characteristics of science.

It is at this point, that it is useful to return to the earlier discussion in this paper of the profound importance of the condition of ignorance, and incommesurability in regulatory appraisal. It was shown there that questions over the scope of appraisal, the plurality of different value positions and framing assumptions, the diversity of different anticipated possibilities and the degree of confidence placed in the available knowledge are all matters that are central to the ‘scientific’ status of the appraisal process. It flows directly from the theoretical foundations of risk-assessment, cost–benefit analysis (and, indeed, all rational choice approaches to decision-making on risk) that probabilistic approaches are inapplicable under strict uncertainty and ignorance. It also follows equally directly from these fundamental theoretical principles that different priorities, framing assumptions and value systems cannot be definitively aggregated across divergent social perspectives. For both these reasons, it is clear that there can be no analytical fix for the definitive ranking of different technology or policy options in the governance of risk. All that can be done to respect principles of scientific rigour in appraisal is to ensure that the process is as broadly framed as possible in terms of the value systems and framing assumptions that are included and the options and possibilities that are addressed. Seen in this way, then, key elements of the ‘breadth’ of the regulatory regime themselves become issues of ‘sound science’ in the governance of technological risk, as well as institutional features of the wider regulatory regime.

Accordingly, Fig. 5 provides a reinterpretation of Fig. 4, with the axes reconfigured to take account of this alternative conception of three of the key characteristics of science in the governance of technological risk. The implications are clear. Whereas under the narrow conception of science in Fig. 4, the ‘scientific’ status of ‘narrow risk’ and ‘precautionary’ approaches were seen to be broadly similar, under the extended notion of risk science in Fig. 5, an asymmetry is introduced. The effect of changing ‘breadth of framing’, ‘recognition of incommensurability’ and ‘acknowledgement of ignorance’ from being features of a broad regime to features of a scientific understanding itself is effectively to rotate the vertical axis in Fig. 5 towards the domain of the precautionary approach. As a result, it becomes evident that under the fundamental theoretical perspective on risk science articulated here,

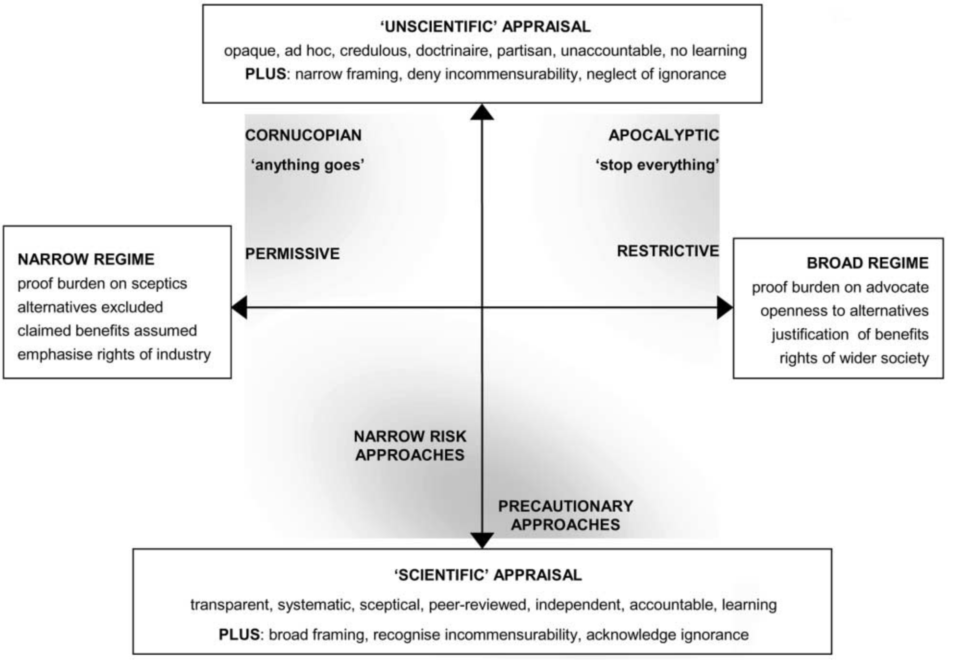

Fig. 5. An alternative model of relationships between risk, science and precaution.

a precautionary approach displaying these three features might arguably be seen to be *more* scientific than the traditional 'narrow risk' approach based on the application of techniques such as risk and cost–benefit analysis.

6. Implications for the governance of technological risk

Although the specific connotations in terms of 'science' and 'precaution' may be quite novel, the general message of this paper is not new. Over recent years, the notion that different forms of environmental and health effect might fruitfully be compared in objectively determinate quantitative terms has fallen under serious doubt. Bodies such as the European Commission [46], the US National Research Council [47], the British Royal Commission on Environmental Pollution [48] and even the UK Treasury [49] have come to acknowledge the intrinsically subjective (and thence political) character of regulatory appraisal. Whilst specialists may often reasonably claim greater authority with respect to the assessment of the likely probabilities or physical magnitudes of precisely specified *individual* effects, it is increasingly recognised that expert judgements are as essentially subjective as any other when it comes to the relative prioritisation of *different* effects. This is particularly the case where decisions are subject to the condition of ignorance. A detailed set of general recommendations for jointly implementing the disciplines of 'science' and 'precaution' in the governance of technological risk are discussed elsewhere by the present author [3]. The present paper will close by highlighting a few of these general principles in the specific context of energy technologies.

Although undermining the ‘objective’ status and credibility of ostensibly precise numerical results, it should not be assumed that the newly emerging consensus on environmental appraisal requires the complete abandonment of the discipline and clarity of quantitative techniques. The implication is simply that they be treated as ‘tools’ rather than as ‘fixes’. Once we are prepared to relinquish the aspiration to unitary definitive ‘results’, the key features of a more realistic approach to the environmental appraisal of energy options seem quite readily identifiable. For instance, simply by treating technological risk as a vector (rather than a scalar) quantity, straightforward *multi-criteria* techniques permit a more systematic approach to the multi-dimensional character of environmental effects. Likewise, numerous tools exist for the substitution of single values expressed to several significant figures with systematic *sensitivity analysis*. Finally, it may be that the problem of divergent assumptions, values and uncertainty might also be addressed by the adoption of a rigorous approach to *diversification*, focusing on portfolios as a whole, rather than on the ‘first-past-the-post’ identification of the ‘best’ individual options [50,51].

Either way, it is clear that an essential but hitherto neglected input to regulatory appraisal is the transparent inclusion of divergent public perspectives and value judgements. In this light, the need for active public participation in the analysis underlying risk regulation is not simply a question of democratic accountability and political legitimacy. It is a fundamental matter of analytical rigour [52].

In response to this emerging new climate in risk governance, a large array of new techniques and procedures are in use in North America and northern European countries for enabling the efficient inclusion of divergent social interests and values at the outset in regulatory appraisal, including citizen’s advisory panels, planning cells, citizen’s juries, ‘study groups’, mediation and regulatory negotiation [53–55]. Although valuable experiments have been conducted in many areas, such techniques have for the most part yet to be seriously pursued on a large scale as a means to inform real policy decisions concerning the governance of technological risk in general, or energy risks in particular.

So what might the social appraisal of energy technology options actually look like, were it to be based on comprehensive and systematic sensitivity analysis under a multi-criteria framework addressing portfolios rather than individual options? A pilot of this type of approach in the hotly contested area of genetic modification is reported elsewhere [56]. Drawing on an earlier schematic study in the energy sector [1], Fig. 6 displays as a set of pie charts the implications for the UK generating mix of adopting a range of perspectives concerning the framing and relative importance of different appraisal criteria. This stylised and purely illustrative exercise models the appraisal of three groups of UK generating options (nuclear, fossil fuels and renewables) under three major classes of environmental risk (land use, air pollution and ‘nuclear issues’). In addition, account is taken of the economic performance of the different options under prevailing market conditions, and of the possibility of deliberately retaining some diversity in the generating mix as a whole. Based on a systematic set of permutations, the 81 different pie charts each represent an electricity supply mix which would be ‘optimal’ for the UK under a particular set of framings and weightings on the various appraisal criteria.

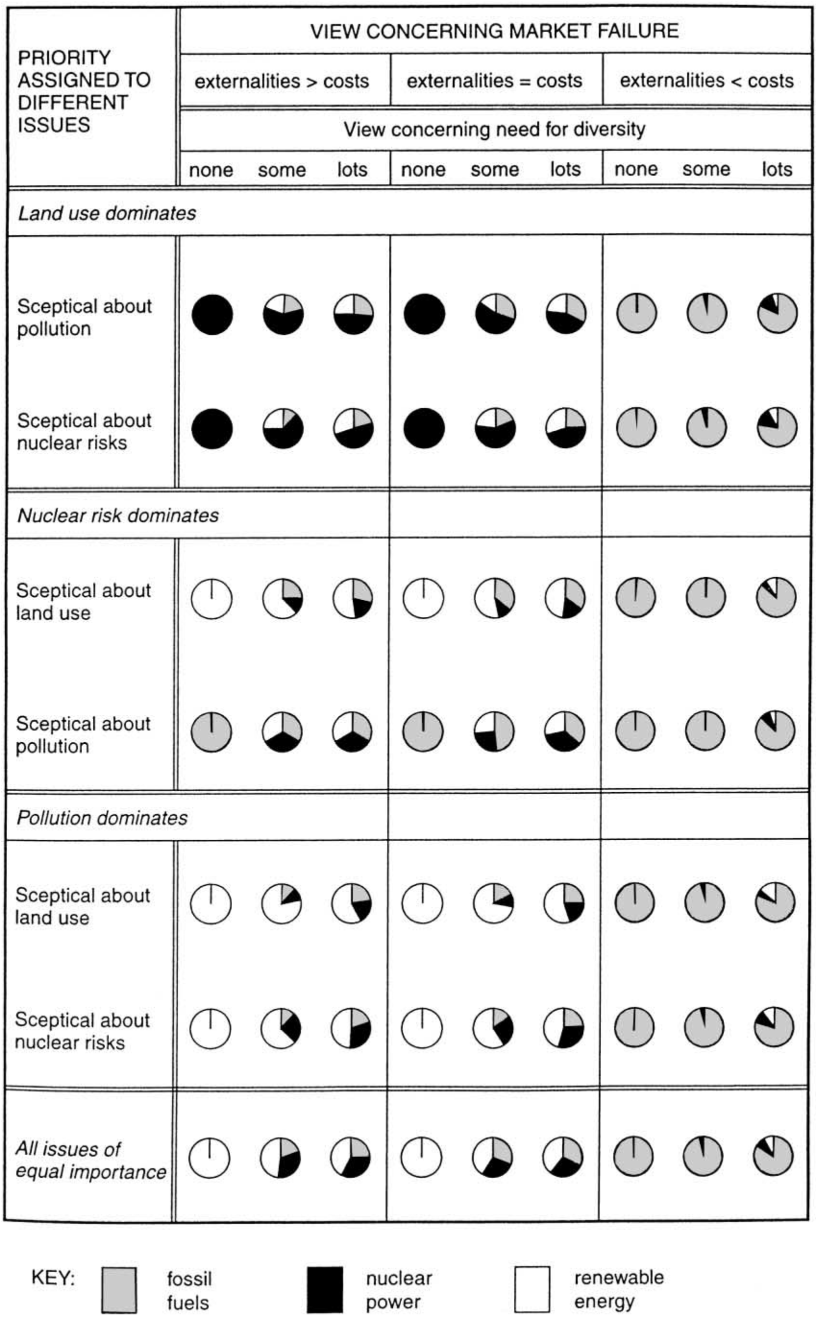

Fig. 6. An illustrative multi-criteria 'sensitivity map', based on a hypothetical exercise.

To the extent that it employs real technical performance data under each criterion and to the extent that the overall range of weighting schemes might be held to accommodate a large portion of the present energy debate, this hypothetical exercise might be viewed as a very rough first order approximation of what the results of a real empirically-based appraisal might look like, were it to be undertaken as part of a formal regulatory appraisal process, or were it to be substituted for one of the many major officially-sponsored regulatory appraisal studies reviewed in this article.

Although just a schematic reflection of a hypothetical exercise, Fig. 6 does serves to illustrate a number of key differences between this sort of broad-based 'precautionary' approach to regulatory appraisal and a narrower 'risk-based' approach using orthodox risk-assessment or cost–benefit analysis.

First, this type of exercise is predicated on an inclusive *participatory* appraisal process rather than on a monolithic 'scientific' analysis conducted exclusively by specialists. Instead of being based on a single position concerning the many dimensions of variability discussed in this paper, this type of appraisal accommodates in parallel a potentially unlimited range of disparate positions.

Second, such a framework offers a far more *transparent* way of dealing with the key dimensions of variability in appraisal. Where results are presented as ostensibly precise discrete numerical values, aggregated under familiar metrics such as monetary value or mortality, attention is drawn away from the fundamental determining importance of the issues discussed in this paper. Under a multi-criteria approach, these factors are all more readily highlighted as the key determining factors in analysis.

Third, and perhaps most importantly, the results are presented as a systematic 'map' of *sensitivities*, rather than as a single prescriptive set of values. Essentially subjective value judgements concerning the relative merits of the disparate forms and distributions of the various effects, variations in the autonomy of those affected, divergent choices of indicators, differences in the treatment of uncertainty and inconsistencies in the framing of analysis are all represented as different 'regions' on this map.

Although there is much more to a precautionary approach than this, what this simple schematic 'thought experiment' does illustrate, is that it is perfectly possible to envisage practical ways in which scientific and precautionary imperatives can be reconciled in the governance of technological risks. The price to be paid for escaping the fundamental practical and theoretical dilemmas, is the adoption of greater humility and pluralism in regulatory appraisal. With recognition of the central role of subjective and contingent interests and value judgements, even in supposedly 'scientific' approaches such as risk and cost–benefit assessment, these crucial aspects of the governance of technological risks can be separated from the narrow technical business of analysis and placed firmly in the domain of politically accountable decision-making where they belong.

Acknowledgements

The author is grateful to fellow participants in a project sponsored by the Forward Studies Unit of the European Commission (addressing 'science and precaution in the management of technological risk'), Andreas Klinke, Arie Rip, Ortwin Renn, Ahti Salo and Silvio

Funtowicz and to numerous other colleagues at SPRU and further afield for helpful commentary over the years on the work summarised here

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