Research Note

S|S|S

Social Studies of Science
42(1) 143–157

DOI: 10.1177/0306312711431836
sss.sagepub.com
SAGE

Precaution: A taxonomy

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Abstract
In this paper we propose a typology of three interpretations of the precautionary principle, each with its associated philosophical and policy implications. We found that these different interpretations of precaution are closely related to variations in the understanding of scientific uncertainty, as well as varying ways of assessing possible (but uncertain) impacts of scientific–technological development. There is a direct link to the question of what scientific knowledge is and what role it plays in regulation and decision-making. The proposed typology permits a conceptual systematization of the current controversies related to the precautionary principle, while facilitating understanding of some of the deeper roots of science and technology policy debates.

Keywords
precautionary principle, risk assessment, risk management, scientific uncertainty, scientific knowledge

An important part of current social and political debates in relation to the protection of human health and the environment focuses on the so-called precautionary principle. This regulatory concept has been adopted in recent years in a wide variety of science- and technology-related pieces of legislation and policy processes, as well as international treaties (de Sadeleer, 2007a; Fisher et al., 2006; Harremoës et al., 2002; Raffensperger and Tickner, 1999; Wiener, 2011). It is a key element in the current regulation of a number of (sometimes controversial) scientific–technological activities and products, but also an important topic in public discourse and debate on science and technology (Stirling, 1999, 2007). It is generally defined as a demand for the protection of health and the environment in the absence of conclusive scientific evidence about the relationship

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between causes and effects (Raffensperger and Tickner, 1999). In this sense, it is an approach to regulatory decisions that differs from classical risk assessment and management (Whiteside, 2006). However, so far there is no general agreement on its interpretation and scope, nor on the specific conditions of its application to policy-making (Murphy et al., 2006; Sandin, 1999; Weiss, 2003).

This lack of agreement has led to a variety of definitions of the precautionary principle, which have been put forward in a number of different contexts. Two examples will be cited here. The first is from the Rio Declaration (Rio Declaration, 1992: Principle 15):

> In order to protect the environment, the precautionary approach shall be widely applied by States according to their capabilities. 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.

The second example is from the European Commission Communication on the Precautionary Principle (European Commission, 2000), which notes:

> The precautionary principle applies where scientific evidence is insufficient, inconclusive or uncertain and preliminary scientific evaluation indicates that there are reasonable grounds for concern that the potentially dangerous effects on the environment, human, animal or plant health may be inconsistent with the high level of protection chosen by the EU [European Union].

Doubts about what precisely is understood by 'precaution' arise in situations in which there is a (perceived) lack of scientific knowledge about a technology's consequences. This lack of specificity leads to varying interpretations of the principle and, ultimately, to controversies over its application. Moreover, it has contributed to a certain radicalization of the predominant views on the precautionary principle.

Two principal positions have emerged (Moreno et al., 2010). Proponents of the principle invoke it primarily to argue for bans (or moratoriums) on certain technologies, such as genetically modified (GM) foods and cell phone antennas in urban areas. In contrast, critics of the precautionary principle consider it to be an unscientific and irrational way of managing technological change (Goklany, 2001; Sandin et al., 2002).

Up to a point, the debate about precaution is inevitable, given that by its very nature the precautionary principle does not provide clear-cut criteria for its application, nor does it prescribe a set of concrete actions. Similar to other legal and regulatory principles, the precautionary principle does not impose a solution but rather creates a new framework within which debates about possible solutions can take place.

For example, the principle may confer legitimacy on arguments that point to a hazard that has not (yet) been clearly established, or on measures (such as post-commercialization monitoring of chemicals) that are introduced because of reasonable doubts about the possibility of determining in advance all the potential implications of a technological innovation. More generally, adoption of the precautionary principle implies 'a shift in science-centered debates on the probability of risks towards a science-informed debate on uncertainties and plausible adverse effects' (von Schomberg, 2006: 34).

However, even though the precautionary principle defines a new framework for conflicts on technological risk regulation, it does not prevent these conflicts. It also allows for discretionary judgment in decision-making, and can be used to justify very different decisions (for instance, decisions to regulate as well as decisions not to regulate a particular technology) (Sandin, 2007; Sunstein, 2005).

Consequently, in this paper we propose a synthesis of the varying interpretations and applications of the precautionary principle. We aim to analyse and classify the different positions and proposals associated with various points of view on the subject. There are three fundamental variables in our taxonomy: scientific uncertainty, the role of scientific knowledge, and management (decision-making).

We identified these variables, as well as the interpretations in our typology, by examining the different formulations of the precautionary principle in controversies over the regulation of technologies such as GM organisms and chemicals. Our analysis also takes into account the academic literature on the subject, including existing classifications of interpretations of the precautionary principle (Klinke et al., 2006; O'Riordan and Cameron, 1994; Renn, 2007; Resnik, 2003; Sunstein, 2005), as well as policy and regulatory documents (European Commission, 2000, 2001, 2006). We explore both the factors underlying these interpretations and the implications they have in several specific regulatory areas.

Because our analysis mainly focuses on the three variables mentioned above – scientific uncertainty, the role of scientific knowledge, and management – we shall give scant treatment to others, particularly the issue of public participation in decision-making (Klinke et al., 2006; Renn, 2007; von Schomberg, 2006). We also do not address questions on the principle's nature, namely its status as a legal rule, a decision rule, an epistemic rule or a guiding principle for action (Peterson, 2007; Renn, 2007; Resnik, 2003; Sandin, 2007; Stirling, 2007). Nor do we address the normative question of how to conceptualize the principle.

Three interpretations of the precautionary principle

From our analysis of the literature on the precautionary principle, we propose that the varying interpretations of the principle are related to:

(1) different interpretations of the scientific uncertainty (or ignorance)[1] associated with possible negative consequences of applying a technology, and the supposed severity of such consequences;
(2) the question of which elements of legitimate judgment apply to these uncertain but possibly harmful consequences; and
(3) the question of the controllability of a technology, or of its (inherent) capacity to impose a particular social agenda or even a structure (a way of life) on society as a whole.

From the predominant applications and formulations of the precautionary principle in academia and policy-making, three (necessarily idealized) interpretations can be extracted (Luján and Todt, 2007) as follows.

Risk-based interpretation

The Risk-Based Interpretation is a moderate interpretation that embodies the idea that any judgment about possible harm has to be based on existing scientific knowledge. Here, the legitimacy of invoking precaution hinges on there being a scientific basis (however incomplete) for suspecting negative consequences. The precautionary principle turns into a guide for risk-based regulation whenever there is a lack of scientific knowledge about risk and it can be suspected that important harm for public health or the environment may ensue. In other words, the precautionary principle satisfies a particular type of demand for risk management, a type which is applicable under certain circumstances (de Sadeleer, 2007b; European Commission, 2000).

Epistemological limits interpretation

The Epistemological Limits Interpretation is an intermediate interpretation that acknowledges the need for scientific, risk-assessment-type analysis, without, however, restricting it solely to standard risk assessment. It points to the existence of uncertainties or even ignorance arising from the inherent epistemological limitations of the very scientific knowledge and methodologies used to assess risk. Consequently, risk assessment and general scientific methodology have to be modified to produce data relevant for decision-making aimed at effectively protecting health and the environment. The precautionary principle in this case is not confined to risk management, but may also exert influence on risk assessment (Tickner, 2003). In fact, authors such as Wandall (2004) argue that, in order to be effective, precaution would already have to be introduced in the risk assessment phase. Introducing precautionary considerations only at the point of risk management (as the European Commission proposes) is understood as being too late in the process to be relevant.

Technology selection interpretation

The Technology Selection Interpretation is a stringent interpretation to the effect that the precautionary principle must be understood either as a principle for selecting technologies (O'Brien, 1999; Tickner, 2008), or as a principle for substituting existing technology with new technology specifically designed to avoid the limitations or problems identified with the existing technology. In both cases the principle turns into an impulse for innovation driven by aims such as minimization of pollution or energy consumption. Classical risk assessment and precaution are seen as two alternative approaches to policy-making, whose main difference lies in the way scientific evidence is applied to decision-making. Any action (and any policy decision) to avoid or severely restrict the use of a technology would have to be justified on the basis of the technology's 'inherent capacity for producing harm'. In sum, the precautionary principle here turns into an alternative to risk-assessment-based risk management (Ashford, 2007; Tickner, 2008). As O'Brien (1999) argues, without analysing alternatives, precaution would essentially be the same as risk assessment. In current policy debates, we can identify the Technology Selection Interpretation particularly among environmentalists.

The European Registration, Evaluation and Authorization of Chemical Substances (REACH) directive[2] provides a good example of different approaches to precaution in

technology policy and practical risk management. REACH has been presented as an inherently precautionary approach to the regulation of potentially dangerous chemicals (Renn and Elliott, 2011). Its drafting, and even more so its recent implementation, has sparked a lot of debate in academia and industry, as well as in regulatory circles.

The European Commission, the administrative body responsible for enacting the REACH directive, advocates a clear separation between risk assessment and risk management (European Commission, 2006). The Commission also interprets the directive's main objective as obtaining information on the toxicity of the chemicals to be regulated. This information would then help in the management of these chemicals, mainly through post-marketing control of their industrial and other uses.

However, not all the social actors who are part of the debate on REACH agree. Actors who subscribe to the Technology Selection Interpretation argue that the directive's main goal is to suppress the use of dangerous chemical substances. Decisions on banning such chemicals would have to be based on a cluster of their 'innate' properties, such as bioaccumulation, persistence and mobility (Winter, 2007). More specifically, proponents of Technological Options Analysis consider that focusing on the generation of information about the toxicity of chemicals to facilitate their post-marketing control is the wrong strategy, because it is time- and resource-dependant and rarely offers definite solutions. What they propose instead is to obtain information on 'inherently safer' alternatives to chemicals that are believed to pose significant risks to human health and/or the environment. The analysis of such alternatives would be based on: (1) the possibility of replacing a particular chemical with a safer alternative, (2) the redesign of the final product, and (3) the identification of the necessary changes in the production process (Koch and Ashford, 2006). The emphasis, therefore, would not be on risk assessment, but rather on risk management, as well as on the possibility of modifying entire technological trajectories.

Some of the positions in the debate on REACH can be classified as examples of the Epistemological Limits Interpretation of the precautionary principle. Proponents of this point of view argue that the most relevant issues are to clarify (1) the information necessary for achieving the explicit objectives of REACH (to ensure a high level of protection of human health and the environment) and (2) the best methods for obtaining such information (Rudén and Hansson, 2010). The case-by-case (chemical-by-chemical) approach of REACH reduces uncertainty about particular chemicals, but does not significantly address the overall uncertainty about risks arising from the 30,000 substances supposedly regulated under REACH. Therefore, these proponents argue, methods are needed for directly reducing overall uncertainty, even when these methods prove not to be very accurate for each individual chemical. Grouping chemicals in categories and analysing those categories' toxicological characteristics is seen as one approach to reducing overall uncertainty (Schaafsma et al., 2009). From this perspective, a methodological change in risk assessment is inevitable if REACH is to achieve its objectives.

Analytical dimensions of the three interpretations of the precautionary principle

As Table 1 shows, the three interpretations of precaution can be characterized systematically by focusing on four analytical dimensions: (1) the origin and nature of uncertainty,

Table 1. An overview of the three interpretations of the precautionary principle

Interpretations of the Precautionary Principle / Dimensions of analysis	Risk-Based (Moderate)	Epistemological Limits (Intermediate)	Technology Selection (Stringent)
Understanding of the origin of uncertainty	(Temporary) lack of scientific data	Uncertainty as an epistemological characteristic of all scientific knowledge	Uncontrollability of (certain) technologies, characterized by their inherent capacity for producing harm
Basis for decision making (factors legitimately used in determining possible harm)	Existing scientific knowledge, even if incomplete	Existing scientific knowledge, but generated or analysed through adapted, diverse methodologies	A list of inherent characteristics of technologies that are deemed to be controllable (i.e., acceptable)
Policy and management	Risk-based regulation (risk management based on risk assessment)	Regulation, based on a wide variety of knowledge generated in a diversity of manners	Technology selection
Implications for Science, Technology and Innovation	Sophisticated process of trial-and-error	Methodological learning in science itself (meta-scientific analysis)	Search for alternative technological solutions

(2) the basis for regulatory decision-making, (3) policy and risk management, and (4) the implications for scientific–technological development and innovation.

The origin and nature of uncertainty

The first analytical dimension for our study of the three interpretations of precaution concerns the reasons why uncertainty is deemed to arise, as well as the role assigned to scientific knowledge in assessing uncertainty. In fact, the understanding of the origin of uncertainty, together with its relationship to the concepts of risk, ignorance, indeterminacy or ambiguity (Stirling, 2007; Wynne, 1992), turns out to be absolutely crucial for interpreting the respective functions that are assigned to precaution in decision-making (Todt et al., 2010).

Under to the Risk-Based Interpretation of precaution, uncertainty arises from a (temporary) lack of scientific knowledge. Therefore, the knowledge necessary to reduce

or eliminate uncertainty, at least in principle, can and will be generated through future research. Since technological trajectories are considered to be flexible, a technology can be steered through regulation. This concept underlies, for instance, the Theory of High Reliability, which proposes that any technology, however complex, can be controlled by means of specific organizational measures (Heimann, 1997). Depending on the magnitude and nature of the possible damage, it is also considered feasible to regulate technology in such a way that the necessary knowledge about its effects is generated during its practical application, for instance by scientific post-marketing analysis. Accordingly, uncertainty can be reduced and possible negative impacts avoided (European Commission, 2000; Foster et al., 2000). However, no major changes are to be introduced in the modus operandi of science (nor risk assessment), as would be the case with the Epistemological Limits Interpretation.

According to the Epistemological Limits Interpretation, scientific knowledge itself is inherently limited as a tool for generating information about technological impacts, especially since the choice of models or the underlying values can decisively influence the results (Douglas, 2000; Shrader-Frechette, 1989). This has important consequences for regulatory decisions. Key epistemological characteristics of scientific knowledge that could reduce the usefulness of science for decision-making include: (1) methodological problems, especially the predominant preoccupation of scientists with Type I, compared with Type II, errors,[3] which results in an excessive emphasis on numerical accuracy in risk assessment to the detriment of rapid decision-making based on available data; (2) affirmation of causal relationships which are open to debate; (3) selection of one of several alternative ways of extrapolating data or applying approximation techniques; and (4) choice and use of models, for instance, in toxicology modelling of dose–response relationships (Cranor, 1995; Douglas, 2000; Shrader-Frechette, 2001). In other words, the way in which science for generating decision-relevant knowledge is carried out would have to be changed profoundly by integrating precaution into the very process of knowledge generation.

In the Technology Selection Interpretation, uncertainty about the effects of a particular technology involves interactions among technology, human actors and the environment. Considered to be the result of a technology's inherent capacity for causing harm (Tickner, 2008), uncertainty in this interpretation is equated with technological complexity (which, in turn, is judged to be beyond any human capacity for control (Perrow, 1984)). It also can be associated with the autonomy of technology in shaping society, an idea arising from the concept of technological determinism. This interpretation of the origin of uncertainty is connected to ideas defended by the Appropriate Technology Movement in the 1970s.

Basis for decision-making

This analytical dimension concerns the criteria that have been put forward for establishing possible harm in situations of uncertainty. More specifically, it concerns the role of scientific knowledge (as well as other sources of knowledge) in risk management. The different points of view on this issue are directly related to the positions on the origin and nature of uncertainty and its relation to scientific knowledge.

In accordance with the advocates of the Risk-Based Interpretation, the relevant decision criterion is 'harm identified on the basis of the scientific knowledge at hand'. Precaution can only be invoked to justify regulatory action if there exists a clear scientific basis for inferring that negative consequences may ensue, even when the relevant knowledge is incomplete (European Commission, 2000). In other words, insufficiency of knowledge does not mean a complete absence of knowledge (Weiss, 2003), and risk assessment remains the basis for regulation and management.

According to proponents of the Epistemological Limits Interpretation, scientific knowledge only can be used as a basis for decision-making when it is generated in a way that takes account of the epistemological limitations inherent in such knowledge, as well as the non-epistemic consequences. This may be done by giving more relevance to Type II than Type I errors (to false negatives instead of false positives), reversing the burden of proof (for instance, through pre-marketing regulation), modifying the criteria for methodological choices (with respect to all kinds of models, methods of extrapolation, dose–response relationships and estimates) or relaxing the standards of proof by applying weight-of-evidence (WOE) approaches, qualitative methods and short-term tests (Cranor, 1995; Haack, 2008; Kriebel et al., 2001; Krimsky, 2005). A further, necessary task is to evaluate in a systematic manner how the concrete results of risk assessment (as well as the regulations arising from them) depend on the chosen methodologies, models, causal frames, approximations and extrapolations.

In other words, the overarching aim of protecting health and the environment becomes a guide for choosing methodologies. This implies putting less emphasis on 'academic' values, such as scientific accuracy (Shrader-Frechette, 2001). As we have already seen, in the Epistemological Limits Interpretation it is precaution itself that drives the very process of generating relevant knowledge for decision-making.[4]

In the case of the Technology Selection Interpretation, the decision criterion requires analysts to establish a technology's inherent uncertainty (with respect to its governability), or its capacity for causing harm. Precaution serves as a guide for decision-making even when there are no data from which to calculate risks. This means that the precautionary principle points to specific characteristics that identify 'acceptable' technologies or technological trajectories, such as flexibility, inherent robustness, reversibility, diversity, adaptability, resilience or controllability (Santillo et al., 1999; Stirling, 1999). Technologies that do not exhibit these characteristics are judged to be 'inherently dangerous', while Technological Options Analysis (Ashford, 2005) suggests 'inherently safe' alternatives.

Policy and management

This analytical dimension deals with the operationalization of the three interpretations of precaution, as well as the related regulatory and decision-making mechanisms. In general, it is important to note that in the Risk-Based Interpretation, the precautionary principle concerns only risk management (but not risk assessment); in the Epistemological Limits Interpretation it concerns both risk assessment and risk management; and in the Technology Selection Interpretation, the precautionary principle turns into an alternative to risk-assessment-based risk management.

Under the Risk-Based Interpretation, regulatory management proceeds along the lines of classical risk management: impacts and risks are minimized through regulations, organizational changes and other efforts to counteract the risks in question. This moderate version of the precautionary principle is the one currently preferred by many policy makers as well as many of the scientists who advise them. In fact, it is the version put forward by the European Commission (2000): only if there are clear indications of possibly dangerous or unacceptable levels of harm should precaution be invoked in policy decisions. This means that the European Commission demands a risk assessment before implementing any regulations guided by the precautionary principle. Existing knowledge, despite its recognized insufficiency, must serve to identify possible harmful effects. The current social debate about GM organisms, for example, shows this with clarity: the European legislation regulating this technology's development and the marketing of GM products (European Commission, 2001) is based on the moderate interpretation of precaution. Regulatory authorities must conduct pre-marketing risk analyses and controlled field trials, as well as scientific post-marketing impact studies, and are required to trace products through the entire chain of production and consumption. The declared aim of these requirements is (1) to be able to identify in a timely fashion unforeseen environmental and health effects, and (2) to generate currently unavailable scientific data on the long-term and large-scale implications of the technology in question (Levidow and Carr, 2000).

The Epistemological Limits Interpretation incorporates precaution into risk assessment itself. In situations in which the inherent limitations of scientific knowledge exercise decisive influence on decision-making, the criterion of 'acceptable uncertainty' replaces the standard risk assessment criterion of 'acceptable risk'. By modifying scientific procedures and explicitly recognizing the underlying values, research guided by this interpretation would take better account of the social and environmental consequences of (1) the limitations inherent to knowledge, and (2) the epistemological and axiological choices made during assessment and analysis. For instance, in standard risk assessment, which centres on establishing probabilities of harm, the relevant epistemic values have traditionally been empirical support and predictive power. However, the Epistemological Limits Interpretation makes possible a relaxation of the standards of proof, while taking other epistemic values into consideration in risk assessment, such as robustness, explicatory power and coherence (Haack, 2008; Resnik, 2003).

As already mentioned, in a number of cases this position proposes the WOE approach as a basis for risk assessment and management. The WOE approach integrates a diversity of lines of evidence (each of which by itself might not be conclusive) in order to support decisions about regulatory options (Krimsky, 2005). A recent example of a regulatory application of this approach is the cleanup of toxic sites (Agency for Toxic Substances and Disease Registry, 2006).

The Technology Selection Interpretation is often defended by environmentalists, as well as scientists close to them. According to this interpretation, only 'inherently controllable' (less complex, flexible, and so on) technologies should be developed further, thereby preventing from the outset any possible negative effects associated with 'inherently dangerous' technologies. Establishing the 'inherent possible harm' of a technology is sufficient for making a decision, as there is no need for detailed assessment of possible

effects or impacts (Santillo et al., 1999). Of the three interpretations, this is the one that assigns least importance to standard risk assessment. In fact, it proposes to substitute debates – open to public participation – about different technological alternatives for debates exclusively concerned with quantitative risk assessment (Ashford, 2007; O'Brien, 1999). This is the predominant precautionary stance adopted by many critics of GM crops and foods. They demand a long-term moratorium or outright abandonment of GM technology because of what they see as uncontrollable environmental and health impacts, as, for example, the practical irreversibility of effects such as gene transfer from modified to non-modified organisms, or the permanent loss of the genetic diversity of important crops such as maize or rice in their regions of origin (Murphy et al., 2006).

Implications for scientific–technological development and innovation

The significance of the diverse interpretations of the precautionary principle becomes clear when we consider the current debates about their effect on innovation, as well as on general science and technology development. For instance, the precautionary approach, even in its moderate (risk-based) forms, has been criticized – often severely – for hindering or even endangering scientific–technological progress (Holm and Harris, 1999; Sunstein, 2005). Consequently, this fourth analytical dimension will allow us to link our previous characterization of the three interpretations of precaution to wider societal questions and debates.

The thrust behind the Risk-Based Interpretation is to protect public health and the environment against possible harm, while at the same time safeguarding innovation against barriers originating from merely speculative or unproven risks and threats; in other words, preventing possible errors from having important negative consequences, without severely curtailing innovation (Todt and Luján, 2008). Here, the development and implementation of new technologies turns into a sophisticated process of trial-and-error, which, obviously, can exert influence on scientific–technological development. Again, the case of GM products serves as an example: EU regulation, while trying to foster biotechnology development by giving it a clear regulatory framework, has shaped the methodological design, case-by-case and step-by-step, of field trials and regulatory reviews. This, in turn, has influenced the way in which industry develops and tests some of its products, including – in specific cases – the introduction of technological modifications (Levidow and Carr, 2000). However, even this rather moderate interpretation of the precautionary principle has been criticized by authors who suggest that the precautionary principle is a process of trial without the possibility of error (implying that no learning can take place if error is not permitted) (Sunstein, 2002; Wildavsky, 2000).

The Epistemological Limits Interpretation clearly has consequences for the process of scientific–technological development: to consider the non-epistemic consequences in risk assessment spawns a process of methodological learning in science. Its aim would be to establish a 'Better Science' (Whiteside, 2006) for improving regulatory decision-making. Shrader-Frechette (2004) calls this a 'meta-scientific analysis'. The proposals to analyse the implications of, for instance, the chosen standards of proof or the rules of inference are examples of such methodological learning. Cranor (2003a) considers this manner of proceeding (including, in some cases, reversing the burden of proof)

indispensable for generating the necessary knowledge about possible effects of new technological innovations.

The implications of the Technology Selection Interpretation for innovation are most visible: this interpretation leads to a systematic analysis of alternative technological options, implying the possibility of de-selecting entire technological trajectories. O'Brien (2003: 280) defines this interpretation as 'goal-driven' precaution (as opposed to 'harm-driven' precaution, as in the first of the interpretations listed in our scheme). The author argues for the need to select 'positive goals' (such as sustainability) and to stimulate the development of technologies (such as green technologies) that further such goals. This position appears to exclude scientific knowledge from decision-making (it has been criticized on this account more severely than the other two interpretations). However, the supporters of technology selection consider that this interpretation, far from being opposed to science, actually supports technological innovation precisely because it implies a systematic and scientific evaluation of alternative options. In fact, the idea that precaution foments innovation for obtaining technologies that entail less uncertainty about their consequences is defended by supporters of all three interpretations of precaution (Tickner et al., 2003).

Conclusion

Although the three interpretations presented here may be understood as mutually exclusive, this is not necessarily the case. In some instances the actors do consider them to be exclusive: The European Commission's own interpretation of precaution, for instance, can be classified within the Risk-Based Interpretation and is clearly aimed at delegitimizing any alternative interpretations of precaution. In a similar way, some of the authors cited earlier in this paper as supporting the Technology Selection Interpretation (for example, Ashford, Santillo and O'Brien) argue that the precautionary principle and risk assessment are mutually exclusive. However, others, such as Tickner, Kriebel and Stirling, consider the second and third interpretations to be compatible with each other: depending on the specific case, as well as the concrete impacts and risks involved, either one can be the more adequate way to regulate a technology.

The classification of the precautionary principle that we proposed in this paper takes account of the varied understandings that social actors display with respect to the concept of scientific uncertainty. How they conceptualize uncertainty about the future impact of technological applications is closely related to their differing interpretations of precaution. However, we are not proposing a causal relationship between such conceptualizations and interpretations. All we can say, on the basis of academic literature and policy documents we reviewed, is that there appears to be a clear and consistent relationship between the two.

The various conceptualizations of scientific uncertainty are consistently related to the role assigned to scientific knowledge in risk management, as well as to its proposed or presumed functions in the governance of technological change. In fact, in each of the three interpretations, science plays a specific (as well as critical) role in framing precaution: (1) as an 'academic science' that serves as an arbiter between regulation and innovation; (2) as a 'precautionary science' specifically tailored to regulatory decision-making;

and (3) as a way to generate 'inherently safe' alternatives. The relationship between innovation, policy and science is reconceptualized in each of the three interpretations, turning precaution into a multi-level and diverse concept.

Our analysis has implications for scientific and social debates on the significance of the precautionary principle. If there is no single interpretation of the principle that is relevant or applicable to all cases, then it may be necessary to revert to one or more particular interpretation according to the characteristics of each individual case, type and level of uncertainty at stake.

Notes

The work presented in this paper was carried out as part of the research projects El principio de precaución en la evaluación de riesgos (HUM2006-12284/FISO) and Las explicaciones basadas en mecanismos en la evaluación de riesgos (FFI2010-20227) of the Spanish Ministry of Science and Innovation. Partial funding of both projects was provided by European Commission FEDER funds.

1. Stirling (1999, 2007) proposes the term 'incertitude' to refer broadly to ignorance about the consequences of technological applications. According to Stirling, the term *incertitude* would include situations of risk, uncertainty and ambiguity, as well as ignorance.
2. In European Commission 'Eurospeak', a directive is a framework of legislation that applies to all member states, but has to be transformed (transposed) into national law in each of them.
3. Avoid, as far as possible, false positives, even though doing so may generate relatively more false negatives (Hansen et al., 2007).
4. Some authors (for instance, Ravetz (1997) and Cranor (2003b) understand the Epistemological Limits Interpretation not so much as a stimulus for methodological change in risk assessment, but rather as a general call for a systematic analysis of the possible consequences associated with the implementation of certain kinds of technologies. In a way, that understanding means a reversal of the burden of proof, and changes the objectives of risk assessment towards analysing possible negative impacts of a new technology.

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