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Late Lessons from Early Warnings: Towards realism and precaution with EMF?

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Abstract

The histories of some well-known public and environmental hazards, from the first scientifically based early warnings about potential harm, to the subsequent precautionary and preventive measures, have been reviewed by the European Environment Agency in their report "Late Lessons from Early Warnings: The Precautionary Principle 1896–2000". This paper summarises some of the definitional and other issues that arise from the report and subsequent debates, such as the contingent nature of knowledge; the definitions of precaution, prevention, risk, uncertainty, and ignorance; the use of different strengths of evidence for different purposes; the nature and main direction of the methodological and cultural biases within the environmental health sciences; the need for transparency in evaluating risks; and public participation in risk analysis. These issues are relevant to the risk assessment of electro-magnetic fields (EMF). Some implications of these issues and of the "late lessons" for the evaluation and reduction of risks from EMF are indicated.

Keywords: Late lessons; EMF; Precautionary principle, Evaluating evidence

1. Introduction

The histories of fourteen well-known hazards and their harm, which include some chemicals: tributyl tin (TBT), benzene, polychlorinated biphenyls (PCBs), chlorinatedfluorocarbons (CFCs), methyl tert butyl ether (MTBE), sulphur dioxide, (SO_2) and Great Lakes pollution; two pharmaceuticals (diethylstilboestrol (DES) and beef hormones); two physical agents (asbestos and medical X-rays); one pathogen (BSE); and fisheries, have been reviewed by the European Environment Agency [1]. The purpose of the review was to see how societies had used, or not, the available scientific information in order to avoid or reduce hazards and risks, and at what overall cost.

Twelve "Late Lessons" were drawn which attempted to synthesise the very different experiences from the case studies into generic knowledge that can help inform decision making on potential hazards from, for example, GMO_S [2,3], nanotechnologies [4], mobile phones [5,6] and such endocrine disrupting substances as phthalates, atrazine and bisphenol A [7–9]. These emerging issues are all cases for which the luxuries of hindsight are not yet available but where there is some plausible evidence of harm, and where exposures are widespread and generally rising.

The purpose of the twelve late lessons is to help societies to make the most of both past experience and current knowledge in order to anticipate and reduce the impact of future "surprises" from technologies, without stifling innovation.

The "late lessons" are reproduced in Box 1 .

2. The early use of precaution

John Graham, who was senior science policy advisor to President Bush, is a critic of the precautionary principle, but has nevertheless noted that:

Precaution, whether or not described as a formal principle, has served mankind well in the past and the history of public health instructs us to keep the spirit of precaution alive and well [10].

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Box 1: "The EEA Twelve Late Lessons"

A. "Identify/Clarify the Framing and Assumptions"

1. Manage "uncertainty" and "ignorance" as well as "risk".
2. Identify and reduce "blind spots" in the sciences used.
3. Assess and account for all pros and cons of action/inaction.
4. Analyse and evaluate alternative options to the agent/activity under scrutiny.
5. Take account of stakeholder values.
6. Avoid "paralysis by analysis" by acting to reduce hazards via the precautionary principle.

B. "Broaden Assessment Information"

7. Identify and reduce interdisciplinary obstacles to learning.
8. Identify and reduce institutional obstacles to learning.
9. Use "lay" and local as well as specialist knowledge.
10. Identify and anticipate "real world" conditions.
11. Ensure regulatory and informational independence.
12. Use more long-term (i.e. decades) monitoring and research.

Graham might have been thinking of the cholera episode of 1854 in Soho, when precaution did indeed serve the people of London well. Dr. John Snow, a well known but controversial London physician, was called in to investigate the cholera outbreak. He used the spirit of precaution to advise banning access to the polluted water of the Broad St. pump, which he suspected was the cause of a serious cholera outbreak. He based his recommendation partly on the evidence he had gathered from his comparative study of two South London populations, who were separately served by piped or well water; and partly on his innovative spatial epidemiological study of the Soho area which pointed to the Broad St. well as the source of water polluted by faeces. He considered this overall evidence was sufficiently strong to justify advising the precautionary action of removing the water pump handle, so that consumers would be forced to use less convenient but cleaner water supplies. His view was accepted by the local church authorities who administered the area.

We know now that Snow's conclusion was accurate. However, his views on cholera causation were not shared by the medical establishment of the day, the Royal College of Physicians and the London Board of Health, who had considered Snow's thesis and rejected it as 'untenable' and biologically implausible [1]. They believed that cholera was caused by airborne, not water borne, pollution. Their scientific "certainty" was increasingly challenged by Snow and others until Koch in Germany finally isolated the cholera vibrio in 1883, thus removing the last remaining doubt about the veracity of Snow's water pollution hypothesis.

The Snow story illustrates many of the key elements of the PP issue that are relevant to today's health and environment controversies, viz conflicting expert advice; competing scientific paradigms; the strength of scientific evidence needed to justify action; the long time lag between *observing* compelling associations and *understanding* their mechanisms of action; and the pros and cons of being wrong in taking action to remove risks, compared to the pros and cons of inaction.

The histories of TBT, PCBs and the other cases in the EEA "Late Lessons" report provide further illustrations of these points.

3. On paradigms and mechanisms of action

Scientists can cling to their favourite paradigm for decades—as with supporters of the air pollution theory in the cholera example between 1854 and 1883, despite mounting evidence that they are likely to be wrong. This passion for the prevailing paradigm is not uncommon. Max Planck, the Nobel physicist noted darkly that old paradigms only really die out when their promoting professors also die: "A new scientific truth does not triumph by convincing its opponents and making them see the light, but rather because its opponents eventually die, and a new generation grows up that is familiar with it" [11].

In similar vein, the IPPC has cautioned the scientific authors of its climate change assessment reports against:

a tendency for a group to converge on an expressed view and become over confident in it. Views and estimates can also become anchored on previous versions or values to a greater extent than is justified [12].

This "power of the prevailing paradigm" is relevant to the current controversy over mobile phones, where the dominant view of WHO, the EU, and many others is that EMF-RF (radio frequency) energy has to be sufficiently large to cause the heating of biological tissue if it is to cause significant harm [13–15]. The current ICNIRP guidelines for limiting unacceptable RF exposures are derived from this paradigm and are therefore:

based on short term, immediate health effects, such as stimulation of peripheral nerves . . . and elevated tissue temperatures [13].

This majority view is opposed by those who think that much lower levels of EMF have the potential to cause harm via their capacity to disturb cell signalling or stress response systems that use very small changes in electro-magnetic fields [16–19].

Is the EMF field witnessing one of those shifts in prevailing paradigms that Thomas Kuhn noted had characterised progress in many fields of science? [20]

It can be difficult to accept that something is happening if you do not understand how it can be happening. A major reason why some scientists hang on to their preferred paradigm when evidence against it is mounting is that they need not only to observe a strong association between a cause and an effect but also to understand the mechanisms of biological action that link them. However, this can take decades. From the *association* between exposure to water polluted with human faeces and cholera, observed by Snow in 1854, to Koch's discovery of the *mechanism of action*, took 30 years of further scientific inquiry.

Such a long time lag between acknowledging compelling associations and understanding their mechanisms of action is a common feature of scientific inquiry, as illustrated by many of the case studies in the EEA report. Biological and ecological understanding about exactly how these exposures caused harm is still absent, decades after the associations were accepted as sufficient to justify preventive actions.

With EMF, there is currently no *established* knowledge about the mechanisms of biological action that could explain the consistent associations between EMF-ELF (extremely low frequency) exposure from overhead electrical power lines and childhood leukaemia. However, there is some evidence of *plausible* biological mechanisms. These include hypotheses concerning "information physics" [21]; melatonin [22]; oxidative stress [19]; indirect effects via cancer promotion; and the radical pair mechanism, which according to the Swedish Radiation Protection Authority, is "*probably the most plausible hypothesised mechanism*" [23]. Some or all of the above mechanisms, possibly in combination with other stressors and genetic configurations, is likely to eventually provide mechanistic explanations for the observed biological effects of EMF-ELF.

Despite this lack of mechanistic knowledge, and a general lack of corroborating animal evidence, the International Agency for Research on Cancer (IARC-WHO) recognised ELF from such magnetic fields as possibly carcinogenic in 2002, based on more than 30 positive epidemiological studies which had been completed since the first "early warning" observation in 1979 [24]. Other scientists do not believe the association between ELF and childhood leukaemias, given the paucity of mechanistic knowledge. However, recent animal and human evidence seems to be filling some of this knowledge gap [25].

The ELF story has parallels with that concerning the ionising X-rays which were routinely given to pregnant women before the early warning of Alice Stewart in the 1950s. She had observed a twofold excess of childhood leukaemias in women given X-rays during pregnancy. Her findings were eventually accepted by the 1970s, despite the continuing absence of knowledge about mechanisms of action: and such routine X-ray exposures were then stopped [26].

The current situation with the EMF-RF exposures from mobile phones is characterised by some positive yet generally inconsistent epidemiological evidence [27–29], by a general absence of animal evidence; and by little established knowledge of possible mechanisms of carcinogenic action.

The question therefore arises: should actions that seem likely to protect the health of the public have to wait for knowledge about mechanisms of action? The precautionary principle was designed to justify actions to protect the public and the environment in the absence of some significant knowledge, and could be used to justify exposure reductions to EMF, despite current gaps in knowledge.

Could the unfolding story of EMF be a repetition of these earlier histories of ionising radiation exposures where evidence of harm was only "established" some twenty or more years after the first early warning?

4. Early warnings

When dealing with newly emerging hazards it can be helpful to use historical examples to illustrate what a scientifically based early warning looks like. It is often difficult to properly recognise such warnings when they occur.

A good example is that provided by the UK Medical Research Council's Swann Committee in 1969. The Committee was asked to assess the evidence for risks of resistance to antibiotics in humans, following the prolonged ingestion of trace amounts of antibiotics arising from their use as growth promoters in animal feed [30]. They concluded that:

Despite the gaps in our knowledge ... we believe ... on the basis of evidence presented to us, that this assessment is a sufficiently sound basis for action ... The cry for more research should not be allowed to hold up our recommendations'....'sales/use of AFA should be strictly controlled via tight criteria, despite not knowing mechanisms of action, nor foreseeing all effects [31].

Despite the gaps in knowledge, the need for much more research, and considerable ignorance about the mechanisms of action, the available evidence was acknowledged by the Swann Committee as sufficient to justify the need for the authorities to restrict the possibility of public dietary exposures to antibiotics from animal growth promoters.

This early warning was initially heeded, but was then progressively ignored by the pharmaceutical companies and regulatory authorities, which wanted more scientific justification for restricting profitable anti-microbial growth promoters. However, the use of antibiotics as growth promoters was finally banned in the EU in 1999, following the lead of Sweden in 1985 [30].

Pfizer, the main supplier of such antibiotics in Europe, appealed against the European Commission decision to ban their product, pleading, inter alia, an insufficiency of scientific evidence. They lost the case at the European Court of Justice [32]. This case further clarified the appropriate use and application of the precautionary principle in circumstances of scientific uncertainty and of widespread, if low, public exposures to a potentially very serious threat.

On EMF there has been a number of early warnings about potential risks at low levels of exposure, culminating in the Bioinitive report of 2007 [33]. This prompted the EEA to also issue an "early warning":

Appropriate, precautionary and proportionate actions taken now to avoid plausible and potentially serious threats to health from EMF are likely to be seen as prudent and wise from future perspectives [34].

It is possible that such early warnings, particularly on RF from mobile phones, issued by the EEA and others, will turn out to be incorrect. This will only be established with time, and the hindsight it brings. However, the EEA would rather be wrong in raising concerns that turn out not to be justified, than being wrong in not issuing an early warning if the potentially serious hazards from RF technology turn out to be real. Large numbers of people are potentially exposed to RF, particularly children who are generally more susceptible to the potential harm. Reducing RF exposures in response to a mistaken early warning is preferable to not reducing exposures to a hazard that turns out to be real, and largely irreversible. Moreover, encouraging such reduction could help to stimulate technical innovation.

5. The importance of timing

The issue of time is a critical issue for risk analysis and application of the precautionary principle.

For example, the time from the first scientifically based early warnings (1896 for medical X-rays, 1897 for benzene, 1898 for asbestos), to the time of policy action that effectively reduced damage, was often 30–100 years, during which exposure increased considerably (Table 1).

One consequence of such failures to act in good time (e.g. on CFCs or asbestos) is greater and irreversible damage over longer time periods. For example, extra natural radiation coming through the ozone hole will cause many tens of thousands of extra skin cancers in today's children but the cancers will only peak around the middle of this century because of the long latent period between exposure and effect. Over a decade's worth of extra skin cancers could have been avoided if action had been taken on the first early warning, (which was subsequently deemed robust enough to justify giving the Nobel prize for Chemistry to its authors), rather than on the discovery of the ozone hole itself. Other negative impacts from the damaged ozone hole include eye cataracts and reduced crop productivity.

Such long-term but foreseeable impacts raise liability and compensation issues, including appropriate discount rates (if any) on future costs and benefits. These issues, which involve value and equity choices, need also to be discussed by stake-

Table 1

Late Lessons chapter	Date of first Early Warning	Date of Effective risk reduction action	Years of substantial inaction
Fisheries: taking Stock	1376	1995–2008 "responsible" management: which is not very effective	Hundreds. . .
Radiation: Early Warnings, Late Effects	1896	1961–1996 UK etc., then EU laws	65
Benzene: occupational setting	1897	1978 Benzene voluntarily withdrawn from most consumer products, US	81
Asbestos: from "magic" to malevolent material	1898	1999 EU ban by 2005	101
PCBs and the Precautionary Principle	1899	1970–80s:EU and US restrictions; phase out by 2010	c. 100
Halocarbons, the ozone layer and the Precautionary Principle	1974	1887–2910 global ban on CFCs + other Ozone depleters	10–30
DES: long-term consequences of pre-natal exposure	1938	1971–1985 US, EU, global ban	30–50
Antimicrobials as growth promoters: resistance to common sense	1969	1999 EU ban	30
SO_2: from protection of human lungs to remote lake restoration	1952 (lung) 1968 (lakes)	1979–2001 increasing EU etc restrictions leading to c 90% reduction on 1975 levels by 2010	25–55
MTBE in petrol as a substitute for lead	1960 taste/odour/persistence in water	2000 undesireable in Denmark/California: permitted elsewhere	40+
Great Lakes contamination	1962/3	1970s DDT banned in N America& EU. 2000 debates continue about persistent health damaging pollution	10–?
TBT antifoulants: a tale of ships, snails and imposex	1976–81 French oysters collapse	1982–7 French, UK then NE Atlantic ban; 2008 global ban	5–30
Beef Hormones as growth promotors	1972/3 oestrogen effects on wildlife	1988 EU ban, US continues	16+
Mad cow disease-reassurances undermined precaution	1979–1986	1989 Partial; 1996 total ban	10–17

holder groups. Experience in the climate change field with these long-term issues [35] may be helpful for the EMF issue.

Timing is also a critical issue for the assessment of risks. Many agents seem to be most damaging during sensitive windows of biological opportunity, either at the foetal stage of development [36], or when the host is susceptible because of an immune response deficiency, or of impacts from other stressors.

Timing is relevant to several biological end points as indicated in a review of the evidence on endocrine disrupting substances:

the time of life when exposures take place may be critical in defining dose–response relationships of Endocrine disrupting substances for breast cancer as well as for other health effects [37].

Responding to these issues of timing involves using lower strengths of evidence to justify action at earlier times in the exposure history of the stressors that inflict damage during specific windows of vulnerability, such as during foetal or early childhood development [38]. The wide exposure of children to EMF brings the timing of actions to reduce exposures into critical focus.

6. Knowledge and ignorance, prevention and precaution

The Broad St. pump example, and the other case studies in the EEA report serve to illustrate the contingent nature of scientific knowledge. Today's scientific certainties can be tomorrow's mistakes, and today's research can both reduce and increase scientific uncertainties, as the boundaries of the "known" and the unknown expand (Fig. 1).

It is common to hear the call for "more research" to remove uncertainties before any actions are taken to reduce hazards. However, such further research may not only take many years but tomorrow's knowledge, in addition to removing some uncertainties, is likely to identify previously unknown sources of both uncertainty and ignorance. These new uncertainties can then be used as reasons for continued inaction on hazard reduction: "paralysis by analysis".

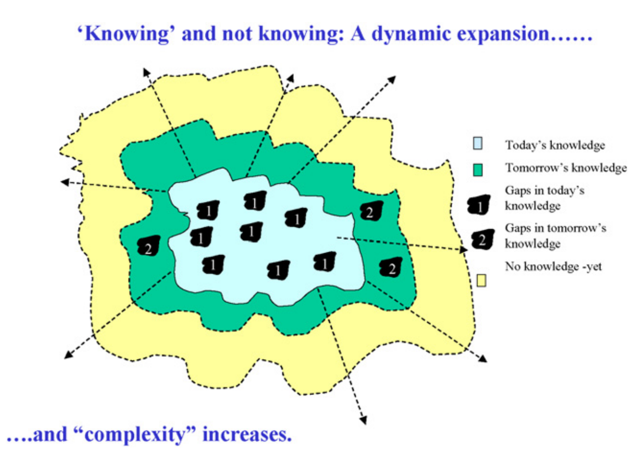

Fig. 1. Knowing and not knowing both espand.

Socrates observed some time ago:

I am the wisest man alive, for I know one thing, and that is that I know nothing [39].

Such an approach to knowledge encourages humility in scientists rather than the hubris demonstrated by those scientists who, for too many years, professed certainties about the absence of harm from X-rays, asbestos, CFCs etc. These "certainties" turned out to be misplaced as knowledge expanded [1].

Many great scientists since Socrates have also displayed much humility in the face of acknowledged ignorance. Isaac Newton provided an elegant illustration of this towards the end of his life of discoveries:

to myself I seem to have been only like a boy playing on the seashore, and diverting myself now and then, finding a smoother pebble or a prettier shell than ordinary, whilst the great ocean of truth lay all undiscovered before me [40].

This was an early lesson in humility that seems to have been lately forgotten by many of the scientists and politicians who deal with hazards to the public and environment.

The distinction between uncertainty and ignorance also has significant implications for risk analysis and management [41]. Uncertainties arise, inter alia, from the known gaps in knowledge, from imprecise exposure sampling and monitoring; and from the assumptions and simplifications of models used to describe complex reality. Scientists involved in regulatory risk assessments try to take account of some of these uncertainties by using arbitrary safety factors to arrive at "acceptable" exposure limits.

Acknowledging ignorance, however, involves acknowledging the unknown unknowns, as well as the sometimes unknowable unknowns that arise from complex and unpredictable biological and ecological systems and the random variations that are common to them [42,43]. It is obviously not possible to just use safety factors applied to "known" associations to account for such lack of knowledge.

States of ignorance are also the source of new scientific discoveries as well as of unpleasant "surprises" such as the mesothelioma cancer from asbestos, the hole in the ozone layer, or the reversed sexuality in the sea snails contaminated by the TBT biocide in marine anti-fouling paints [44].

Foreseeing and preventing hazards in the context of ignorance presents particular challenges to decision-makers. Ignorance ensures that there will always be surprises, and at first sight it looks impossible to do anything to avoid, or mitigate, them. However, there are some measures that could help minimise the consequences of ignorance and the impacts of surprises:

- using the intrinsic properties of potential stressors as generic predictors for unknown but possible impacts e.g.

the persistence, bioaccumulation and spatial range potential of chemical substances [45];
- reducing specific exposures to potentially harmful agents on the basis of credible 'early warnings' of initial harmful impacts, thus limiting the size of any other 'surprise' impacts from the same agent, such as the asbestos cancers that followed asbestosis; and the PCB neurotoxicological effects that followed its wildlife impacts;
- promoting a diversity of robust and adaptable technological and social options to meet human needs, which then limits technological 'monopolies' (such as those of asbestos, CFCs, PCBs etc.), and therefore reduces the scale of any 'surprise' from any one technological option;
- accepting significant biological and ecological effects, such as inflammatory responses, or changing sex ratios, as sufficient evidence of potentially adverse effects to justify hazard reduction, without waiting for the adverse effects themselves to arrive;
- using more long-term research and monitoring of what appear to be "surprise sensitive sentinels", such as frogs, bees and foetuses, in order to identify "early warnings" earlier;
- using scenarios and stakeholder involvement to help foresee and anticipate implications of particular technological and social pathways.

Some of these approaches are relevant to EMF.

The distinction between *prevention* and *precaution* is also important. Preventing hazards from "known" risks is relatively easy and does not require precaution. Banning smoking, or asbestos, today requires only acts of *prevention* to avoid the well-known risks. However, it would have needed *precaution* (or foresight, based on a lower strength of evidence), to have justified exposure reductions to the then uncertain hazards of asbestos exposure in the 1930s–50s, or of tobacco smoke in the 1950s–60s.

Such precautionary acts then, if implemented successfully, would have saved many thousands of lives and, in the case of asbestos, stimulated innovation in the insulation and other asbestos using industries decades earlier than has been the case.

Similarly, it would need precaution to justify reducing exposures to an IARC category two carcinogen, such as EMF, but only prevention to avoid the cancer risk from a class one carcinogen, such as ionising radiations, where the evidence for action is very well established.

There has been much debate generated by the different meanings attached to these and other terms commonly used in debates on hazards, such as "prevention", "precaution", "risk", "uncertainty" and "ignorance". Table 2 attempts to clarify these definitions, using some of the "Late Lessons" case studies as illustrations.

There is also frequent confusion between the *strength of evidence* needed to justify any action to reduce risks, and the *type of action* deemed to be appropriate: the two are not directly connected. For example, there is very strong evidence that cars harm people, but they are not banned from most places. In contrast, slight evidence of possible birth defects arising from taking a pregnancy pill would usually be sufficient to justify banning that pill.

7. The precautionary principle: some definitions and interpretations

The Vorsorgeprinzip, (the "precautionary", or "foresight") principle, only emerged as a specific policy tool during the German debates on the possible role of air pollution as a cause of "forest death" in the 1970–80s.

An increasing awareness of ecological complexity and uncertainty during the 1980–90s led to debates on the Vorsorgeprinzip shifting from Germany to the international level, initially in the field of nature conservation [46] but then particularly in marine pollution, where an overload of data accompanied an insufficiency of knowledge [47]. This absence of knowledge generated the need to act with precaution to reduce the large amounts of chemical pollution entering the North Sea.

Since then over 60 international treaties, including the Third North Sea Ministerial Conference, 1990, have included reference to the precautionary principle, or, as the Bush negotiators prefer to say, the precautionary approach. (A recent legal review points out that there is little, if any practical difference between these two concepts [48].)

The Treaty of the European Union cites the precautionary principle thus:

Community policy on the environment ... shall be based on the precautionary principle and on the principles that preventive action should be taken, that environmental damage should, as a priority, be rectified at the source, and the polluter should pay [49].

Although only cited in the environment part of the EU Treaty, the precautionary, prevention and polluter pays principles also apply to health and consumer affairs, as European Court of Justice decisions have made clear [50].

Unfortunately, these principles, as well as the important and legally required *proportionality principle*, which limits disproportion between the costs and benefits of precaution or prevention, are not defined in the EU Treaty. However, their usage has been clarified in over 100 court cases [48].

A definition of the precautionary principle that is often cited by supporters and detractors alike is that from the The North Sea Declaration, which calls for:

action to avoid potentially damaging impacts of substances, even where there is no scientific evidence to prove a causal link between emissions and effects (my emphasis).

Critics of the precautionary principle claim that this definition appears to justify action even when there is "*no scientific evidence*" that associates exposures with effects. However, the N. Sea Conference text clearly links the words "no scien-

Table 2
Towards a clarification of key terms.

Situation	State and dates of knowledge	Justification for action
• Risk	Known' impacts; 'known' probabilities e.g. asbestos 1999	*Prevention*: action taken to reduce known hazards e.g. eliminate exposure to asbestos dust
• Uncertainty	'Known' impacts; 'unknown' probabilities e.g. antibiotics in animal feed and associated human resistance to those antibiotics 1999	*Precautionary Prevention*: action taken to reduce exposure to plausible hazards e.g. ban antibiotic growth promotors
• Ignorance	'Unknown' impacts and therefore 'unknown' probabilities e.g. the 'surprise' ozone hole from (CFCs), pre-1974	*Precaution*: action taken to anticipate, identify and reduce the impact of 'surprises'

Source: Amended from the "Late Lessons" report, EEA 2001.

tific evidence" with the words "to prove a causal link" (my emphasis).

We have already seen with the Broad St. pump example that there is a significant difference between the evidence needed to show an "*association*" between a pollutant and its harm, and evidence which is robust enough to "prove" a *causal* link, which requires a very much higher strength of evidence. Bradford Hill pointed this out in his classic paper on association and causation in public health which he wrote at the height of the smoking controversy [51].

The N. Sea Declaration says that the absence of the strong evidence needed to support causality is not a valid reason for inaction where there is widespread and potentially hazardous exposures and some plausible evidence of potential harm.

Despite increasing use of the precaution principle there is still much disagreement and discussion about its practical application. This is particularly due to the absence of an EU definition in regulatory texts, and to disputes over the sufficiency of scientific evidence needed to justify public policy action.

For example, many "definitions" of the precautionary principle or approach in the 60 or so Treaties and Conventions that now include this concept use a triple negative: that is, they identify the *absence* of strong scientific evidence (e.g. of "full" certainty") as a reason that *cannot* be used to justify *not* acting, And they do not specify what a sufficiency of evidence would be that could justify taking action.

Some other widely cited definitions of the precautionary principle, notably the Wingspread and UNESCO definitions, are rather long, and include items that are not strictly part of a definition, such as the *process* by which decisions are taken (i.e. participatory, or not); and the allocation of the *burden of proof* to risk makers or risk takers: the latter is a separate issue that societies have dealt with without recourse to the precautionary principle.

For example, European and other societies have long placed the pre-market burden of establishing reasonable grounds for the safety of medicines, pesticides, nuclear plants and large construction projects on those who wish to provide such products or projects, Other potentially harmful agents, such as the 100,000 or so existing chemicals in consumer products, have been placed on the market without such pre-market burdens. Although pre-market testing or assessment is more precautionary than post market surveillance, it does not require justification from the precautionary principle.

There have been further definitions and clarifications of the precautionary principle from, for example from the EU Council of Ministers; in EU case law; and in the regulation establishing the new European Food Safety Authority, EFSA [52].

The judgement of the European Court of Justice in the BSE case illustrated a general definition which many authoritative commentators consider contains most of the necessary elements of the precautionary principle:

Where there is uncertainty as to the existence or extent of risks to human health, the institutions may take protective measures without having to wait until the reality and seriousness of those risks become fully apparent [53].

The WHO Declaration from the Fourth Ministerial Conference on Environment and Health [54] also refers to the precautionary principle. An explanatory background paper recommends that the principle:

should be applied where the possibility of serious or irreversible damage to health or the environment has been identified and where scientific evaluation, based on available data, proves inconclusive for assessing the existence of risk and its level but is deemed to be sufficient to warrant passing from inactivity to policy alternatives [55].

A recent report from the Health Council of the Netherlands on the precautionary principle provides a clear and cogent summary of the issues raised by its use [56].

However, there remains an absence of a clear definition at EU level so the European Environment Agency (EEA), in response to the debates on the precautionary principle since its 2001 report, has produced a working definition of the precautionary principle.

The Precautionary Principle provides justification for public policy actions in situations of scientific complexity, uncertainty and ignorance, where there may be a need to act in order to avoid, or reduce, potentially serious or irreversible threats to health or the environment, using an appropriate level of scientific evidence, and taking into account the pros and cons of action and inaction [8].

The definition is proving useful in promoting a shared understanding of the precautionary principle. It is explicit in specifying both uncertainty and ignorance as contexts for applying the principle; it is couched in the affirmative rather than the negative; and it explicitly acknowledges that a case specific sufficiency of scientific evidence is needed to justify public policy actions, given the pros and cons of action or inaction.

The definition also explicitly widens the conventionally narrow, and usually quantifiable, interpretation of costs and benefits to embrace the wider and sometimes unquantifiable, "pros and cons". Some of these wider issues, such as loss of public trust in science, are unquantifiable, but they can sometimes be more damaging to society than the quantifiable impacts: they therefore need to be included in any comprehensive risk assessment.

But what is "an appropriate strength of evidence" that would justify taking action under the precautionary principle to reduce exposures and risks?

8. Establishing evidence for action

All serious applications of the precautionary principle require some plausible evidence of an association between exposures and current, or potential, impacts.

For example, the Communication from the EU on the precautionary principle [57] specifies that "reasonable grounds for concern" are needed to justify action, but it does not say that these grounds will vary with the specifics of each case: nor does it explicitly distinguish between risk, uncertainty and ignorance.

The strength of scientific evidence that would be appropriate to justify public action clearly must vary with the pros and cons of being wrong with action or inaction in the specific circumstances of each case. These circumstances include the nature and distribution of potential harm; the justification for, and the benefits of the agent or activity under suspicion; the availability of feasible alternatives; and the overall goals of public policy. Such policy goals can include the achievement of the "high levels of protection" of public health, of consumer safety, and of the environment, required by the EU Treaty.

The use of different strengths of evidence for different purposes is not a new idea.

For example, a high strength of evidence such as "beyond all reasonable doubt" is used to achieve good science where A is generally accepted as causing B only when the evidence is very strong. Such a high level of proof is also used to minimise the costs of being wrong in the criminal trial of a suspected murderer, where it is usually regarded as better to let several guilty men go free, when reasonable doubt about their guilt cannot be eliminated, than it is to wrongly convict an innocent man.

However, in a different trial setting, where a citizen seeks compensation for harm that is possibly due to negligent treatment at work, the courts in many European and other societies will use a lower strength of evidence, commensurate with the costs of being wrong in this different situation. An already injured party is given the benefit of the doubt by the use of a medium level of proof, such as "balance of evidence, or probability". This is justified on the grounds that it is more acceptable to give compensation to someone who was *not* treated negligently than it is to *not* provide compensation to someone who was treated negligently. The "broad shoulders" of insurance companies are seen as able to bear the costs of mistaken judgements rather better than the much narrower shoulders of an injured citizen.

In each of these two illustrations it is the nature and distribution of the costs of being wrong that determines the strength of evidence that is "appropriate" to the particular case, based essentially on ethical grounds. The choice of an appropriate strength of evidence in each case is therefore a societal not a scientific issue.

This has long been recognised. Bradford Hill, cited above, drew attention to the social responsibility of scientists whose work involves public health. He concluded his classic 1965 paper on association and causation in environmental health with a "call for action" in which he also proposed case specific and differential strengths of evidence.

His three illustrative examples ranged from "relatively slight" to "very strong" evidence, depending on the nature of the potential impacts and of the pros and cons of being wrong. These varied between a possibly teratogenic medicine for pregnant women; a probable carcinogen in the workplace; and government restrictions on public smoking or diets [51].

In the field of cancer, the International Agency for Research on Cancer also uses several types of scientific evidence to categorise their strengths of evidence on carcinogens [58].

Identifying an appropriate strength of evidence has also been an important issue in the climate change debates. The International Panel on Climate Change (IPCC) discussed this issue at length before formulating their 1995 conclusion that "on the balance of evidence" mankind is disturbing the global climate. They further elaborated on this issue in their 2001 report where they identified seven strengths of evidence that can be used to characterise the scientific evidence for a particular climate change hypothesis. By 2007 the evidence for human induced climate change had strengthened to a "reasonable certainty" [59].

Table 3 provides the middle 5 of these strengths of evidence from the IPPC and illustrates their practical application to a variety of different societal purposes.

In the risk assessments of EMF published so far there has been little explicit discussion about the choice of the strength of evidence used in the assessments. The vague term "no established evidence" is often used to characterise the absence of some strength of evidence that would convince the particular scientists doing the risk assessment that a hazard existed. There is little if any discussion about for whom the evidence is said to be not established (risk takers or risk makers), nor about for what purpose (warning labels, or low cost exposure reductions, for example.).

Table 3
Different levels of proof for different purposes.

Different levels of proof for different purposes: some examples and illustrations

Probability	Quantitative descriptor (Probability bands based on IPCC 2001)	Qualitative descriptor	Illustrations
100% probability	Very likely 90–99%	• "Statistical significance"	• Part of strong scientific evidence for "causation"
		• "Beyond all reasonable doubt"	• Most criminal law. And the Swedish Chemical law, 1973, for evidence of "safety" of substances under suspicion-burden of p roof on manufacturers
	Likely (66–90%)	• "Reasonable certainty"	• Food Quality Protection Act, 1996 (US)
		• "Sufficient scientific evidence"	• To justify a trade restriction designed to protect human, animal or plant health under World Trade Organisation Sanitary and Phytosanitary (SPS) Agreement, Art. 2.2, 1995
	Medium Likelihood (33–66%)	• "Balance of evidence"	• Intergovernmental Panel on Climate Change 1995 & 2001
		• "Balance of probabilities"	• Much Civil and some administrative law
		• "Reasonable grounds for concern"	• European Commission Communication on the Precautionary Principle 2000
		• "Strong possibility"	• British Nuclear Fuels occupational radiation compensation scheme, 1984 (20–50% probabilities triggering different awards up to 50% + , which then triggers full compensation)
	Low Likelihood (10–33%)	• "Scientific suspicion of risk"	• Swedish Chemical law, 1973, for sufficient evidence to take precautionary action on potential harm from substances-burden of proof on regulators
		• "Available pertinent in formation"	• To justify a provisional trade restriction under WTO SPS Agreement, Art. 5.7 where "scientific information is insuffiicient"
	Very Unlikely (1–10%)	• Low risk	• Household fire insurance
		• "Negligible and in significant"	• Food Quality Protection Act, 1996 (US)

Source: EEA (2002).

An exception is the Californian EMF-ELF risk assessment which was much more transparent and explicit about these critical issues [60].

Establishing a sufficiency of evidence for whom, and for what purpose, involves value judgements: such issues therefore require public participation.

9. Public participation in risk analysis

Choosing an appropriate strength of evidence for a particular case is not a scientific issue but a social choice. It is therefore necessary to involve the public in decisions about serious hazards and their avoidance: and to do so for all stages of the risk analysis process, as recommended by several authorative bodies during the last 10 years [61,62,63,64,56,65]. Three of the "twelve late lessons" of the EEA report (numbers 5, 9 and 10 in Box 1) also encourage the involvement of stakeholders at all stages of risk analysis.

Fig. 2 based on the above reports, illustrates the iterative nature of risk assessment, risk management, and risk communication; the links between them; and the involvement of stakeholders at every stage, albeit with different intensities.

The existing International and European arrangements for risk analysis, and for the setting of public exposure limits for EMF and other issues such as food [66], do not seem to reflect these recommendations for opening up the process of risk analysis, including risk assessment, to stakeholder participation. Instead they largely retain the older, linear approach where risk assessment is separated from risk management and communication and where communication is largely one way, i.e., from scientists to managers to the public.

The best available science is therefore a necessary but not a sufficient condition for sound public policy making on potential threats to health and the environment, such as from EMF. Where there is scientific uncertainty and ignorance "it is primarily the task of the risk managers to provide risk assessors with guidance on the science policy to apply in their risk assessments" [67]. The content of this science policy advice, as well as the nature and scope of the questions to be addressed by the risk assessors, need to be formulated by the

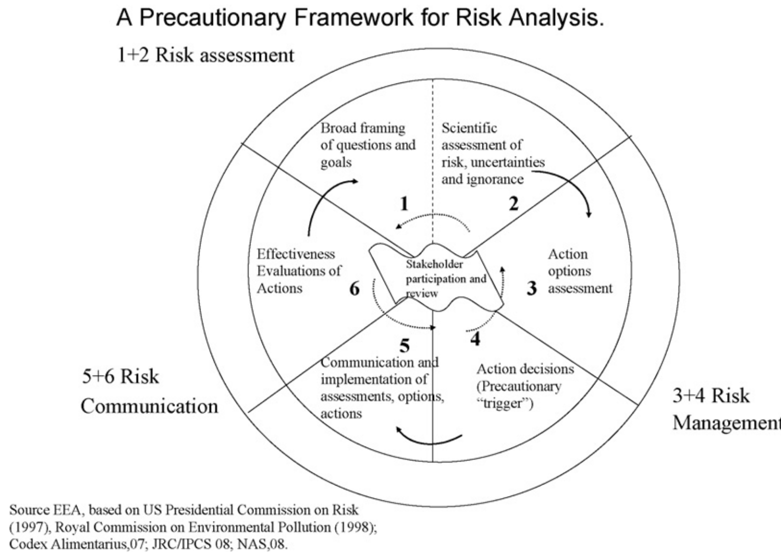

Fig. 2. A Precautionary risk analysis framework.

risk managers and relevant stakeholders at the initial stages of the risk analysis, as indicated in Fig. 2.

It is not easy to involve the public in all stages of risk analysis and in helping to set associated research agendas and technological trajectories [68,69]. However, there are some useful experiences, in both Europe and the USA, with focus groups, deliberative polling, citizens juries, and extended peer review, which are exploring appropriate ways forward [70,71].

The SAGE stakeholder process in the UK, which focused on ELF from power lines, provides a useful illustration of stakeholder engagement [72].

Public participation is particularly essential when future technological and social pathways, and associated hazards, are unpredictable: being wrong together is more socially robust than letting experts alone make the mistakes.

But why are there enough "mistakes", from delayed policy actions to prevent serious harm, to fill several volumes of Late Lessons reports?

10. False positives and false negatives

The fourteen case studies in the Late Lessons Report are all examples of "false negatives" in the sense that the agents or activities were regarded as not harmful for many years before evidence showed that they were harmful. Attempts were made to include a "false positive" case study in the report (i.e. where actions to reduce potential hazards turned out to be unnecessary), but neither authors nor sufficiently robust examples were found.

Providing evidence of "false positives" is more difficult than with "false negatives" [73]. For example, how robust, and over what periods of time, does the evidence on the absence of harm have to be before concluding, with confidence, that a restricted substance or activity is without significant risk?

Volumes 2 of "Late Lessons", which the EEA will publish in 2009, will explore the issues raised by false positives, including lessons to be learned from such apparent false positives as the EU ban on food irradiation and the hazardous labelling of saccharin in the US [74].

But why are there so many "false negatives" that have been so damaging to health or environment? And how might this be relevant to EMF?

The first Late Lessons volume of case studies provided two main answers: the bias within the health and environmental sciences towards avoiding "false positives", which thereby generates more "false negatives": and the dominance within societal decision-making of short term, specific, economic and political interests over the longer term, diffuse, and overall welfare interests of society. The latter point needs to be further explored, particularly by the political sciences: the current and increasing dominance of the short term in markets and in parliamentary democracies makes this an urgent issue.

Since the publication of "Late Lessons" the EEA has further explored the second cause of "false negatives" i.e. the issue of bias within the health and environmental sciences. Table 4 lists eighteen common features of methods and culture in the environmental and health sciences and shows their main directions of error. Most tend towards generating "false negatives".

Table 3 is derived from papers presented to a conference on the precautionary principle organised by the Collegium Ramazzini, the EEA, the WHO and NIEHS in 2002 [75]. It tries to communicate the main directions of the biases within the environmental and health sciences which decision makers and the public should be aware of as they debate the evidence on emerging hazards such as EMF.

Table 4
ON BEING WRONG: Environmental and health sciences and their main directions of error.

Scientific studies	Some methodological features	Main[a] directions of error-increases chances of detecting a:
Experimental	• High doses	• False *positive* (negative for low dose effects)
Studies	• Short (in biological terms) range of doses	• False negative
(Animal Laboratory)	• Low genetic variability	• False negative
	• Few exposures to mixtures	• False negative
	• Few Foetal-lifetime exposures	• False negative
	• High fertility strains	• False negative (developmental/reproductive endpoints)
Observational	• Confounders	• *False positive* (negative with multi-causality?)
	• Recall bias	• *False positive*
Studies	Inappropriate controls	• *False positive*/negative
(Wildlife & Humans)	• Non-differential exposure misclassification	• False negative
	• Inadequate follow-up	• False negative
	• Lost cases	• False negative
	• Simple models that do not reflect complexity	• False negative
Both	• Publication bias towards positives	• *False positive*
Experimental and observational studies	• Scientific cultural pressure to avoid false positives	• False negative
	• Low statistical power (e.g. From small studies)	• False negative
	• Use of 5% probability level to minimise chances of false positives	• False negative
	• Much scrutiny of positive studies cf. negative studies	• False negative

[a] Some features can go either way (e.g. inappropriate controls) but most of the features mainly err in the direction shown in the table.

11. Towards realism about complex reality

Max Planck observed that "reality is . . . just a very thin slice of that vast range of what our thoughts try to encompass" [76]. EMF scientists and risk assessors need not only to take account of the false negative/positive biases described above but they should also take more account of "that vast range" of other realities which characterise the EMF issue. These include multi-causality; thresholds; timing of dose; sensitive sub-populations; sex, age, genetics, and immune status of the host; cumulative exposures to EMF and other stressors; information physics; effects below the thresholds of such "acute" impact as tissue heating; non-linear dose–response relationships; "low dose" effects; the absence of unexposed controls; and the effects arising from disturbing the balance between opposing elements in complex biological systems, i.e. the "harmony of opposites" which Heraclitus noted many centuries ago.

In the EMF debate these complexities are often subsumed under many simplifying assumptions. For example, the WHO review of power line ELF states that:

Based on known physical principles and a simplistic biological model, many authors have argued that average magnetic fields of 0.3–0.4 micro tesla are orders of magnitude below levels that could interact with cells or tissues and that such interactions are thus biophysically implausible [77].

In the context of expanding scientific knowledge, the "implausibility" of biological interactions may not be a robust basis on which to dismiss positive epidemiological or experimental observations, especially when the biological models being used are "simplistic".

The case studies in the EEA report illustrate the surprises that arise from real life ecological and biological complexities and which may carry some lessons for the EMF debate. For example, the unfolding of the TBT story was accompanied by an increased appreciation of scientific complexity. This arose from the discoveries that the known acute effects provided no indication of the chronic impacts that were caused by very low doses (i.e. in parts/trillion); that high exposure concentrations were found in unexpected places e.g. in the marine micro-layer; and that bioaccumulation in higher marine animals, including sea-food for human consumption, was much greater than expected. The early and prescient actions on TBT exposure reduction in France and the UK in 1982–85 were based only on a medium 'strength of evidence' for the 'association': evidence that was sufficient to infer 'causality', or to identify 'mechanisms of action' came much later.

We were lucky with TBT: a highly specific, initially uncommon impact (imposex) was quickly linked to one chemical, TBT. This is not likely to happen with the multi-causal and more common impacts such as neurodevelopmental diseases and dysfunctions, or cancers, which are the more complex impacts from EMF that are under suspicion.

Some key lessons from the DES story are also relevant to EMF exposures [78].

These include the realisation that the absence of visible and immediate teratogenic effects is not robust evidence for the absence of reproductive toxicity; and the timing of the dose clearly determined the poison, in contrast to the conventional dictum in toxicology, articulated by Paracelsus, that 'the dose determines the poison'.

DES is now a well-studied compound, with over 20,000 publications, yet many doubts persist about its mechanisms of action more than 30 years after it was banned on compekking observatory evidence that has since become more so. If we still have few biological certainties about DES after so much time and research, what should our attitude be towards relatively little understood hazards, such as other endocrine disrupting substances and EMF?

The scientists and risk assessors of EMF need not only to acknowledge the "surprises" that arise from complex realities but also the asymmetry of measurement precision between gene typing and environmental exposure assessment. As Vineis has observed, such asymmetry is likely to lead to an underestimation of the effects of environment and an overestimation of the effects of genes in the gene/environment interactions that are involved in most public health issues, including EMF [79].

The research implications arising from multi-causality, and from the systemic interactions between genes, host conditions and environmental stressors, seem not to have been fully recognised in the environmental and health sciences.

Sing has noted that:

neither genes nor their environments, but their interactions, are causations .... pretending that the aetiology of common diseases like CHD, cancer, diabetes and psychiatric disorders are caused by the independent actions of multiple agents is deterring progress [80].

He went on to call for:

"research that reflects the reality of the problem" and notes that "a reductionist approach that has no interest in complexity discourages imaginative solutions ... we need an academic environment that puts greater value on how the parts are put together".

Such a systems approach to multiple and cumulative stressors seems to be largely absent from much research and risk assessment of EMF. Recent progress in dealing with cumulative stressors in the chemical field may be of use to EMF scientists [81].

12. Towards transparency in evaluating "weight of evidence"

Since 1965 overall evaluations of scientific evidence for policy making on health hazards has often, implicitly or explicitly, been based on the nine, "Bradford Hill Criteria", which Bradford Hill actually called "features" of evidence [51]. These were produced in response to the smoking and health controversy of the 1960s.

One of the apparently more robust of the nine "criteria", consistency of research results, which is a much discussed issue in the current EMF debate, may not be so robust in the context of multi-causality, complexity and gene/host variability.

Prof. Needleman, who provided the first of what could be called the second generation of early warnings on lead in petrol in 1979, has subsequently observed that:

Consistency in nature does not require that all or even a majority of studies find the same effect. If all studies of lead showed the same relationship between variables, one would be startled, perhaps justifiably suspicious [82].

It follows that the *presence* of consistency of results between studies on the same hazard can provide some of the robust evidence needed to establish a causal link, but the *absence* of such consistency may not provide very robust evidence for the absence of a real association. In other words, the "criterion" of consistency is asymmetrical, like most of the other Bradford Hill "criteria".

This is relevant to the current position with EMF where consistent research results are not generally available. Such inconsistency is to be expected, particularly at this relatively early stage in the complex biological and physical story of EMF.

There is great scope for legitimate differences of view about this and other implications of the complexity, uncertainty and ignorance that characterise the EMF debate. Judgements need to be made, for example, about the weights to be placed on the presence or absence of features of the evidence, such as consistent research results, mechanisms of action, and animal evidence. There is therefore likely to be wide divergences of scientific opinions between different groups of scientists who evaluate the same stock of scientific knowledge during their risk assessments.

For example, in 2000, the UK National Radiological Protection Board set up the Stewart Committee to evaluate the evidence on mobile phones. It concluded that the evidence for safety was not great; that the evidence for harm was weak, but that this was to be expected at this early stage in the history of mobile phones; that the numbers of people, especially young people, exposed was widespread and rising; and that the precautionary principle was relevant, and justified the recommendation that mobiles phones ought not be used by children under 16, except in emergencies [5].

During the same year, a radiation advisory Committee under the Dutch Health Council, comprising similarly qualified scientists, evaluated the same stock of knowledge and concluded that the evidence for safety was robust; that the evidence for harm to RF exposure was largely absent; that children were not more sensitive to RF exposures from mobile phones than adults; and that the precautionary principle was not relevant: no action on exposure reduction was therefore justified [83].

In order to tease out the different and largely hidden assumptions and inferential rules adopted by the two committees, the EEA organised a workshop in May 2008 at which representatives of the two committees explained how they came to such divergent opinions. They were joined by scientists who had produced different evaluations of essentially the same knowledge in three other case studies: ELF from power lines; the plastics chemical, bisphenyl A; and pesticides spray drift.

A brief report summarising the EEA workshop, and containing an eighteen-point checklist that identifies the main reasons for such divergences of view is now available [84].

There appears to be very few risk assessments of EMF that are transparent about how their largely implicit assumptions, judgements and rules of inference affected their conclusions.

An exception is the Californian Department of Health Services evaluation of the possible risks from ELF power line exposures [60]. This report was transparent about its graduated approach to strengths of evidence, about the weights that the individual scientist involved in the assessment placed on different types of evidence, and their types of argumentation and their rules of inference. The assessment was longer and more resource consuming than other EMF risk assessments but its transparency, and stakeholder involvement in agreeing the approach to evaluating the evidence, seems to have produced a more socially and scientifically robust assessment. The recent report from the US National Academy of Sciences on Risk Assessment strongly recommends such transparency and stakeholder involvement, especially at the crucial problem framing stage [65].

13. Conclusion

The successful application of available scientific knowledge and of the precautionary principle to public policy-making on health and environment involves several issues that have been identified in, or have arisen from, debates over some late lessons from early warnings that the EEA has identified. Such issues include the contingent nature of knowledge; approaches to uncertainty, ignorance and "surprises"; appropriate strengths of evidence for policy actions; the biases in the environmental health sciences; public participation in risk analysis and in choices over innovation pathways: and the need for more realism and transparency in the evaluation of evidence about complex ecological and biological realities.

These issues are particularly relevant to the potential hazards that are now emerging from, inter alia, nanotechnology, where scientific ignorance predominates [85]; from the non-ionising radiations arising from the use of mobile phones and power lines; and from endocrine disrupting substances. Such issues require new approaches that, inter alia, involve elements of what has been called post normal science [86].

The capacity of "homo sapiens" (who should perhaps be called, with less hubris, "homo stupidus" as few, if any other species, consciously destroy their habitats) to foresee and forestall disasters, appears to be limited, as the EEA reports on late lessons illustrate.

Societies could, however, with more humility in the face of uncertainty and ignorance, heed the late lessons and, aided by a wider, yet wise application of the precautionary principle, anticipate and minimise hazards. In so doing they would stimulate more participatory risk analysis and governance; the use of more realistic and transparent systems science; and the development of more socially robust and technologically diverse technological and social innovations.

Three main scenarios seem to face us with EMF, particularly with the RF from mobile phones. The first is similar to the case studies in the EEA reports on late lessons, where much avoidable harm was not prevented. The second is where precautionary actions to reduce EMF exposures avert much potential harm, whilst stimulating more sustainable innovation in the production and use of mobile phone technologies and energy systems. And the third is where such precautionary actions to reduce exposures are taken but they turn out to have been unnecessary, if reasonable, given the state of knowledge today. The choice is ours: to act or not to act, as Shakespeare might have said.

Disclaimer

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