Science Advice for Policy by European Academies

MAKING SENSE OF SCIENCE

FOR POLICY UNDER CONDITIONS OF COMPLEXITY AND UNCERTAINTY

SAPEA
Science Advice for Policy by European Academies

Evidence Review Report No. 6

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A list of the experts who contributed to the report is available in Annex 7.

In accordance with Article 35, paragraph 1 of the aforementioned Grant Agreement, the Consortium identified all relevant interests of the experts requested to contribute to the Evidence Review Report, assessed whether an interest constituted a conflict of interests, and took — where relevant — measures to exclude that an interest could compromise or be reasonably perceived as compromising the impartiality or objectivity of the report. Further information about SAPEA's working processes are available at www.sapea.info/guidelines.

This report can be viewed online at: www.sapea.info/making-sense-of-science

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Making sense of science for policy under conditions of complexity and uncertainty

Informs the European Commission Group of Chief Scientific Advisors' Scientific Opinion 7 (forthcoming)

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About SAPEA

SAPEA (Science Advice for Policy by European Academies) brings together outstanding expertise in engineering, humanities, medicine, natural and social sciences from over 100 academies, young academies and learned societies across Europe.

SAPEA is part of the European Commission's Scientific Advice Mechanism. Together with the Group of Chief Scientific Advisors, we provide independent scientific advice to European Commissioners to support their decision-making. We also work to strengthen connections between Europe's academies and Academy Networks, and to stimulate debate in Europe about the role of evidence in policymaking.

The Evidence Review Report informs the GCSA's Scientific Opinion on the topic (forthcoming), which will be available here:
http://ec.europa.eu/research/sam/index.cfm?pg=science

Funded through the EU's Horizon 2020 programme, the SAPEA consortium comprises Academia Europaea (AE), All European Academies (ALLEA), the European Academies' Science Advisory Council (EASAC), the European Council of Academies of Applied Sciences, Technologies and Engineering (Euro-CASE), and the Federation of European Academies of Medicine (FEAM).

For further information about SAPEA, visit www.sapea.info

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Foreword

In the twenty-first century, we face extreme global challenges like climate change, population growth and widespread pollution, as well as contending with major change brought about by technological advances. As a result, science advice has consistently come to be regarded as a vital element in the overall evidence considered by policymakers. At the same time, policymakers are striving to make sense of scientific evidence that is most certainly complex, multifaceted and, quite often, at the very limits of what is known scientifically. It is against this backdrop that the European Group of Chief Scientific Advisers (GCSA) decided to address the question of how to provide good science advice to European Commission policymakers.

SAPEA was delighted to be asked to undertake a comprehensive evidence review, which informs the Scientific Opinion of the GCSA. Both reports are published simultaneously. *Making sense of science for policy under conditions of complexity and uncertainty* is the fifth Evidence Review Report to be published by the SAPEA consortium, an integral part of the European Scientific Advice Mechanism.

In drafting this report, SAPEA formed an outstanding working group of European experts from a variety of disciplines, backgrounds and countries. All were determined to bring together the many schools of thought on the topic, as well as their extensive practical experience in science advice, and to reach a position of consensus. Their success in this endeavour is reflected in this Evidence Review Report, which highlights the unique role played by science in effective policymaking. We are confident that the report and its summaries will be useful to policymakers in Europe, and beyond.

We would like to thank everyone involved, and express our sincere gratitude to those who have contributed directly to the report, above all, the members of the Working Group and its excellent Chair, Professor Ortwin Renn.

Professor Sierd Cloetingh

Chair of the SAPEA Board, 2018-2019

President of Academia Europaea, 2014-2020 (Lead Academy for *Making sense of science for policy under conditions of complexity and uncertainty*)


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Key to the report

All terms underlined are defined in Annex 4.
All abbreviations used are listed in Annex 5.

Preface

Making sense of science for policy is an unusual title for an evidence review report. The term 'sense-making' is clearly related to interpretation and cannot be covered without reference to individual or social judgements. In short, what makes sense to one person may not make any sense at all to another. While there are, in each society, shared understandings of what certain phenomena mean, there is no universal arbiter who would be able to distinguish between 'correct' or 'incorrect' sense-making. What is more, the nature of what science can offer to policymakers depends on the basic understanding and shared concepts of mandate, validity, reliability and relevance of scientific statements in the respective policy arena. As much as empirical studies can describe and classify different models and procedures of how scientific advice has been brought into policymaking arenas, they cannot provide conclusive evidence of which model of science advice has worked more effectively, or even better than another. Such a judgement would imply that there are objective success or failure criteria by which scientists could measure the degree to which a specific criterion has been met. However, this is not the case.

What can be measured are either the levels of experienced satisfaction of all the actors involved in scientific advice to policymakers, or the degree of impact in the form of outputs (i.e. immediate results) and outcomes (i.e. the policy changes brought about). However, judgement on whether these impacts are a 'success' or a 'failure' differs considerably among those who make the judgements, including scientific communities themselves (B. G. Peters, 2017). Again, there is no objective authority that could make this judgement, based on empirical evidence. Most evaluations of science advice for policymaking therefore combine procedural criteria that are related to the quality of the process (such as comprehensiveness of information, fairness to all participants, competent review of knowledge claims, and others) with subjective assessments performed by the participants or affected outsiders (Royse, Thyer, & Padgett, 2016, pp. 99 and 193). Such evaluations have been systematically considered in our report, but it is important to state from the beginning that while these studies provide us with useful hints about the appropriate quality criteria for successful models of science advice, they provide no firm, let alone conclusive, evidence of what constitutes success or failure. The choice of criteria, as well as the measurement of how well they have been met, is always a combination of empirical results and interpretation where, in this domain, interpretation is an even stronger component of reaching conclusions than in other domains of the empirical sciences.

Given the importance of interpretation and judgement, it is no surprise that there are many different schools of thought on the study of science and science advice. These provide quite distinctive answers to the question of what science is (or should be) and how it can be best used for policymaking. As stated in the Introduction and Chapter 2, there are different concepts coming from the philosophy of science, from the sociology of science, from the study of knowledge and many other traditions. They are often not compatible with each other and result in different interpretations of the same factual material. Most pronounced is the division between realist (science explores how nature and the world functions) and constructivist/relativist concepts (science provides constructions or relationships between mental models and signals from the outside world filtered through our senses or instruments). These two concepts have dominated the epistemic debate in the respective disciplines for a long time and, due to the controversial positions of many advocates on both sides, are difficult to reconcile (Rouse, 1996). However, the group of experts convened to write this report was convinced that this confrontational period has now passed and therefore a more pragmatic view on how to view science and its role in policymaking is called for.

Given these conditions, the following report is deliberately written with the common understanding that:

1. The topic of sense-making cannot be addressed adequately by looking at the empirical evidence only; it rather requires room for interpretation and (inter-)-subjective judgement.
2. The question of what counts as a 'success' or a 'failure' of scientific advice for policymaking cannot be determined without referring to interpretation and judgement. There are certainly valuable indicators for selecting, classifying and ordering outputs and outcomes but interpreting this descriptive data requires experiential knowledge (familiarity with the topic) and prudent judgement. That is why several members of the expert group referred to their immediate personal experience with mechanisms of policy advice in parts of the report.
3. The experts convened to write this report were motivated to overcome the traditional schisms between different schools of thought in this area and composed a report that is based on a pragmatic, consensus-oriented interpretation of the literature and familiarity with the various traditions and schools of thought.

As a consequence of these propositions, the following report differs from the other evidence review reports so far produced by SAPEA. It includes, wherever possible, evidence from the empirical study of advice processes. It also refers to and cites interpretations and conceptual thoughts of many scholars devoted to studying the nexus between science and politics (which in themselves are also interpretations and not 'hard' evidence). Yet many conclusions that are drawn in this report, particularly in Chapter 6, constitute more than a mere compilation of empirical evidence and interpretations from the literature; *they are the results of a creative process of combining empirical evidence, insights from the literature and personal reflections by those who have been active in giving scientific advice for many years*. Such an amalgamation of sources is, in our view, inevitable for this topic, as one can only cover the topic of sense-making by using a method that makes sense in itself.

Professor Ortwin Renn

Chair, SAPEA Working Group on *Making sense of science for policy under conditions of complexity and uncertainty*

Executive Summary

The need for science advice

1. Science[1] advice to today's policymakers has become more prominent than ever, due primarily to the growing human impact on our world, and the ever-increasing complexity of the knowledge needed for coping with economic, social and environmental challenges. These include demographic changes, global trade issues, international market structures, transboundary pollution, digitalisation, urbanisation and many other factors of modern life. Many such policy problems are characterised by a mixture of complexity, uncertainty and ambiguity. The issues for which scientific input is most needed by policymakers are the ones for which the science is most often complex, multidisciplinary and incomplete.

2. Scientific expertise supports effective policymaking by providing the best available knowledge, which can then be used to understand a specific problem, generate and evaluate policy options, and provide meaning to the discussion around critical topics within society. Scientific knowledge is crucial to ensuring that systematic evidence is part of the collective decision-making process. Systematic knowledge is instrumental to understanding phenomena, providing insights that help to understand and tackle society's problems. Science therefore represents an essential element in Europe's future development of policy.

3. The nature of science advice is wide-ranging. The science advisory ecosystem includes a broad set of players, from individual academics to national academies, universities, think tanks and many others. Their roles include knowledge generation, synthesis, brokering, policy evaluation, horizon scanning and more.

4. In the vast majority of policy cases, scientific advice is only one of many inputs but it occupies a unique position, as summarised below and in the report.

The purpose of our report

5. This SAPEA Evidence Review Report draws on the work of a group of European experts from many disciplines and many countries. Our Evidence Review Report supports the work of the European Group of Chief Scientific Advisors (GCSA), which has published a Scientific Opinion on *Making sense of science for policy under conditions of complexity and uncertainty* (Scientific

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[1] We adopt a broad definition of 'science', closer to the German term *Wissenschaft* than the English understanding of the term 'science'. Our definition is intended to include the social sciences and humanities, as well as the important contributions of the natural sciences, engineering and mathematics to robust and effective policy processes.

Advice Mechanism, 2019). The GCSA's Scientific Opinion is addressed primarily to policymakers who utilise scientific advice across the European Commission, and is also of relevance to the governance of scientific advice in the Commission. The overarching question posed by the GCSA is:

> How to provide good science advice to European Commission policymakers, based on available evidence, under conditions of scientific complexity and uncertainty?

The structure of our report

6. This report has four main chapters. In Chapter 2, the report introduces some of the key terms that are the building blocks for the rest of the report. Chapter 3 explores the prospects, limitations and constraints of scientific advice for policymaking. Chapter 4 illuminates the policymakers' needs for scientific input and advice. Chapter 5 addresses the potential for enhancing the interface between scientific evidence and policymaking. The report concludes with a summary of the main findings, in the form of lessons learned.

The debate about science

7. There are many schools of thought in the study of science and science advice that provide quite distinctive answers to the question of what science is or should be, and how it can be best used in policymaking. These come from the philosophy of science, the sociology of science, the study of knowledge and many other traditions in the field.

8. Members of the SAPEA expert group are motivated to overcome traditional schisms between different schools of thought in this area. The report is based on a pragmatic, consensus-oriented interpretation of the published literature and familiarity with theory and practice. The report includes, wherever possible, evidence from the empirical study of advice processes, but it also refers to and cites interpretations and conceptual thoughts of many scholars devoted to studying the nexus between science and policy.

9. Most concepts of science agree that its purpose is to produce and test claims about reality. It includes statements that are descriptive (how reality is shaped), analytic (causal and functional relationships between phenomena) and, depending on the specific discipline, normative (how reality should be changed or altered).

10. Systematic knowledge is generally generated and evaluated according to established rules and conventions of the respective academic discipline. These rules are not perfect, yet they are regarded as superior to any other alternative.

The role of science in policymaking

11. Scientific experts provide knowledge that helps to provide evidence to the policymaking process. 'Evidence' can be defined as a knowledge claim that is backed up by a recognised scientific procedure or method.

12. Scientific knowledge and understanding represent an essential dimension of many policy decisions. The contributions of scientists to policymaking should be encouraged and valued. Scientific advice is neither arbitrary, nor is it a direct representation of an objective 'truth'. At its best, it is based on methodological rigour, agreed-upon rules of enquiry, systematic review of evidence, and continuous analysis and debate.

13. Science advice must be based on the best available evidence, communicated in a transparent and accountable way that explicitly and honestly assesses uncertainties, ambiguities and tensions.

14. In the current climate of populism, 'post-truth' and 'fake news', public scrutiny and the accountability of science are an inevitable and even desirable aspect of democratic processes.

Bringing science advice to policy

15. Methodological rigour that seeks to attain valid, reliable and robust evidence remains the most important means of judging the quality of scientific insights.

16. Many policy options require systematic knowledge that is not available, or still in its infancy, or in an intermediate state. There may be an incomplete understanding of the phenomenon and no clear causal relationship; it may rely on educated guesses by experts. These all need to be labelled as such and it is essential to demarcate the limits of 'reasonable' claims.

17. Making sense of science cannot be done by only looking at the empirical evidence. On the contrary, it requires lots of room for interpretation and inter-subjective judgement. The question of what counts as the 'success' or 'failure' of scientific advice for policymaking cannot be determined by objective measurements. There are many valuable indicators, but interpreting such descriptive data requires experiential knowledge (i.e. familiarity with the topic) and prudent judgement.

18. Scientific outputs often represent the best available systematic knowledge on a given subject, but this is not the only relevant or necessary knowledge that decision-makers should use. Knowledge based on actual experience and local perspectives can often be provided only by people, who share common experiences with the policy issue under consideration. The term 'evidence-informed', rather than 'evidence-based', therefore assures that all evidence is considered but does not become the sole basis for decision-making.

19. What counts as 'good' evidence varies with the questions: it depends on what policymakers want to know, for what purpose, and to what context the scientific advice is being addressed. Most practices on the presentation of evidence and its appraisal are focused on social values of legitimacy, trust, impartiality and credibility.

20. Complexity is a major barrier to providing reliable insights about the likely consequences of decision options. Examples of highly complex phenomena include climate change and economic crises. Individual scientists may not be able to see the entire picture, but experts from different disciplinary perspectives can give policymakers a more complete picture of what science knows and does not know, and about the robustness of available evidence.

21. In the context of decision-making, uncertainty relates to a situation with more than one outcome consistent with expectations. Scientific uncertainty relates to the limitedness or even absence of scientific knowledge (i.e. data and information) that makes it difficult to assess the exact probability and possible outcomes of unwanted effects. Uncertainty management and quality assurance are essential in any decision-making process. Scientific uncertainty can be communicated effectively by characterising, assessing and conveying the limits of scientific statements clearly. In particular, it is necessary to ensure that policymakers understand the meaning of probability distributions, confidence intervals and statistical quality criteria when interpreting uncertainty characterisations and are well-informed about the assumptions and conventions that are incorporated in various scientific assessments.

22. While more and better data and information may reduce scientific uncertainty, more knowledge does not necessarily reduce ambiguity. This report uses the term 'ambiguity' to represent the plurality of scientifically justifiable viewpoints on the meaning and implications of scientific evidence.

Conclusions of the report

23. The conclusions in the report are the results of a creative process of combining empirical evidence, positions from the literature and personal reflections by those who have been active in giving scientific advice for many years. These are:

- **Science advice can help to anticipate future challenges and assist in designing coping strategies or interventions** in a world in which human actions have become the dominant force in shaping it (the Anthropocene era).
- **The focus of science advice must be on a critical review of the available evidence and its implications for policymaking**. It is important that scientific advice is based on evidence that is respected as valid, relevant, reliable and (depending on the academic discipline involved) replicable. It should include a quantitative assessment or, if that is not possible or feasible, a qualitative

characterisation of scientific uncertainty and ambiguity. Some of the EU agencies have made progress in this area, and it would be a welcome initiative if guidance and best practice were shared.

- **Scientific advice should not prescribe but inform policies.** Any political decision needs to consider the likely consequences of decision options (where scientific input is essential) as well as the social, political and moral desirability of these consequences (where plural values and ethical principles play a major role). In the end, any scientific advice may turn out to be incomplete, contested or even unsubstantiated. The selection and interpretation of evidence must be guided by the articulation of different social values and legitimate interests, involving not only advisers and decision-makers, but also additional stakeholders and civil society.
- **The purpose and significance of scientific advice depend on the issue and the context.** There are many forms and sources of knowledge. Science advisers should see their role as important, and also as a unique source of robust and reliable knowledge, but not as the exclusive providers of knowledge. When policymakers and science advisers agree in advance on the role and function that scientific evidence should play, it should lead to greater clarity and collaboration.
- **Form and function are vital when designing appropriate policy-science interfaces.** There is no universally applicable model for structuring scientific advice for policymaking. The type or nature of available expertise and the type of advice needed should determine the procedure, structure and composition of the advising process.
- **Science advice for policymaking involves many legitimate perspectives and insights.** Defining 'the issue' and selecting the most appropriate expertise requires judgement and vision. For complex problems and issues, it is essential that the complete range of scientific opinions is represented and that all uncertainties and ambiguities are fully disclosed.
- **Scientists, as well as policymakers, should be sensitive to various biases and interests** when drawing inferences from data and information. Having access to different disciplinary perspectives (for example, the humanities, natural sciences etc.) can act as a check and balance procedure to address unintended bias.
- **Science advice is always affected by values, conventions and preferences.** Rather than highlighting the role of the 'objective' knowledge provider, the science-policy nexus is better served when both sides are transparent about what values and goals they apply and how knowledge claims are selected, processed and interpreted. This creates more trust and confidence in institutions and in the processes for science advice.
- **The effectiveness of scientific advice depends on the right composition of advisers and the quality of the dialogue between advisers and policymakers.** Science advice should include evidence that clarifies and explains the factual content of an issue, including a characterisation of its robustness and validity, together with the ethical and societal impacts of the topic and the values involved. When translating evidence and

research findings, issues such as transparency, openness, assumptions and uncertainties must be addressed and communicated. Advisers should accept some level of responsibility in advising and in the implementation phase of their advice. Feedback on the effects of the advice is needed, which can be used for adjustments or correcting actions during its implementation.

- **The relationship between science advisers and policymakers relies on mutual trust.** It is important to maintain a capacity for reflection, as well as openness on the part of policymakers to disruptive advice.
- **The most highly recommended science advice process combines analytic rigour with deliberative argumentation**. Analysis refers to the inclusion of systematic and peer-reviewed knowledge. Deliberation refers to the mutual exchange of arguments and reflections, to arrive at evidence-informed and value-balanced conclusions in a discussion.
- **Stakeholders and citizens should be integrated into the process.** Continuous forums for deliberations between the scientists, the public and policymakers should be fostered. Critical elements to be considered include the transparency of aims, the means of power regulation between the different stakeholders, and responsive communication strategies.
- **Science advice is not limited to policymakers but includes science communication to the wider society**. Effective science communication includes clarity about the quality of evidence, the treatment of uncertainties and ambiguities, the possible courses of action and information about the background of the science advisers themselves. Effective partnerships between scientists, policymakers and practitioners (who implement policy decisions) will help to build trust and credibility.

Chapter 1: Introduction

In an era of contested truth claims and widespread discontent with policymaking, scientific input to public discourse and collective decision-making seems to be more required than ever. However, the nature of what science can and should offer to decision-makers has been under rigorous scrutiny by philosophers and sociologists of science. This report draws upon the work of a group of European scientists from many disciplines and many countries. In focusing on the relationship between science advice and policy, they found themselves debating several rather profound questions. How useful is scientific knowledge for public decision-making? What other forms of knowledge and understanding are required within democratic policy processes? Should scientific understanding be regarded as universal in its reach and scope, or is that understanding dependent on context and situational conditions? Perhaps at the most fundamental level of all, what status should be given to scientific knowledge within sometimes polarised and controversial issues; should it be treated as one source of evidence among others, or does it possess a special standing and significance? Concepts such as *transformative*, *transdisciplinary* or *co-creative research* and *extended peer communities* elucidate the direction in which the debate about the nexus between science and society is moving.

As might be expected within such a diverse group, the participants did not always agree on the answers to these questions. Beyond the legitimate diversity of positions about the role of science for policy advice, all members of the expert group shared the view that the relationship between science advice and public policy is more important than ever. Science represents an important element within Europe's future development. More specifically, and without claiming that it should be the only input, scientific knowledge is crucial to ensuring that systematic evidence is part of the public decision-making process. Furthermore, the group agreed on the following common propositions.

1. Firstly, the group adopted a broad rather than a narrow definition of 'science', closer to the German term *Wissenschaft* than the English understanding of the term 'science'. Whilst discussions of 'science' often draw attention to the important contribution that the natural sciences, engineering and mathematics can make to robust and effective policy processes, the group emphasised the role to be played by the social sciences and humanities. In making this point, the group also indicated the cross- (or pluri-)disciplinary nature of many of the challenges posed within contemporary policy processes. Put very generally, the contributions of philosophers, economists, anthropologists and other representatives of the social and cultural sciences are, in principle, as essential as those of physicists, chemists, biologists and others from the natural sciences.

2. The second area of agreement relates to the current climate of populism, 'post-truth' and what is often referred to as 'fake news'. Public challenges to the legitimacy of truth claims and expert statements can be a sign of a healthy

and open society — and this may include questions, for example, about the source of research funding or the assumptions embedded in allegedly neutral scientific statements. Such public scrutiny and accountability regarding science is an inevitable — and even desirable — aspect of democratic processes. However, the dismissal of expert statements simply on the grounds that they are produced by experts who may disagree with the implications of special interests or world views, and are therefore not to be trusted, is deeply problematic. Without reverting to crude notions of 'speaking truth to power', scientific knowledge and understanding represent an essential dimension of many policy decisions and the contribution of scientists to policymaking should be encouraged and valued, rather than swept aside. It may be entirely reasonable to debate, question and challenge specific forms of scientific evidence. Yet, the group strongly advocates evidence-informed policymaking — even if the precise structure and operation of this need careful consideration (as the rest of this report will discuss). Scientific advice is neither arbitrary, nor a direct representation of an objective truth. At its best, it is based on methodological rigour, agreed-upon rules of enquiry, systematic search for evidence, and continuous review and debate.

3. There is a third area of agreement. In preparing this report, the group debated the type of distinction that Alvin Goldman (1986, 1988) draws between 'weak and strong justification' and its connection with the standards and criteria used to justify different knowledge claims. Science frequently requires strong justification; scientific claims are expected to be subject to peer review, to be publicly available, and to be open to sceptical scrutiny and processes of verification or falsification. Everyday claims of knowledge, the claims that govern much of our lives, sometimes require less rigorous forms of justification, but they too are answerable to justificatory norms. As discussed later in this report, there are different styles of reasoning within science and beyond, and it is important to respect separate disciplinary and methodological traditions and norms of justification that apply to them. The perspective in this report, however, is that there is more that is shared across even a broad definition of science than divides it.

   This does not mean that science has the answer to every policy problem. There are certainly many questions asked with regard to policy matters where science might be able to provide part of the picture, but certainly not the entirety (as Alvin Weinberg (1972) captured many years ago in his concept of 'trans-science'). However, it is the common perspective of all experts in the group that science can make an essential contribution to many policy matters, provided appropriate conditions are made available for this. The group thus adopted a pragmatic, but also constructive, approach to the application of scientific evidence to pressing societal and environmental challenges. Thus, while the group acknowledged different schools and traditions in discussing the role of science in policy decisions, in particular, the so-called 'realist vs. constructivist' debate on the nature of truth in science, the report adopts a pragmatic approach where the success of a scientific theory, compared to other available options, is judged in reference to its explanatory and predictive powers. The main contribution of science to policy advice is to improve decision-making in a complex environment, and this report will try to provide and interpret the insights from theoretical and empirical studies on the conditions and requirements for making the science-policy nexus meet this major objective.

4. This leads to a fourth area of agreement. It is important to consider the relationship between science and policy not only as a matter of a theoretical or philosophical debate, but also in terms of the evidence as it has been compiled over many years by scholars, key institutions and engaged parties. In searching for successful or less successful examples for policy-science interfaces, there has been a growing body of evidence that is complex and multifaceted. As pointed out in the Preface to this report, what may count as success or as failure is also contested. The outcome of a consultation between scientists and policymakers does not always point in one direction. This report attempts to take stock of the variety and richness of viewpoints as it affects this topic. Of course, not everything can be covered in this report. However, it is the conviction of the whole group that this evidence review, enriched with the experiential knowledge of the group members, can provide a solid foundation for informed reflection and improved practice.

Based on these agreements, the Evidence Review Report is structured into five chapters. After this Introduction, Chapter 2 introduces some of the key terms that are the building blocks for this report. Chapter 3 explores the prospects, limitations and constraints of scientific advice with regard to policymaking. The focus here is on the contributions of scientific knowledge in its various forms for public decision-making. In Chapter 4, the Evidence Review Report explores the users' needs for scientific input and advice. If the needs of policymakers are misinterpreted or not met, the main objective of 'successful transfer of evidence into policymaking' is certainly missed. What are the needs of decision-makers in politics, economics and civil society when they look for external expertise and competence? What can science advice offer to assist decision-makers in tackling wicked problems (see Sections 2.2 and 5.2 for more details) and resolving complex problems? Chapter 4 analyses the various functions of scientific expertise for policymaking and describes the conditions and structural requirements for meeting policymakers' demands and improving communication.

Based on the potential contributions of scientific expertise in the policymaking process, and the needs of policymakers for robust knowledge, Chapter 5 outlines how to design the interactions between policymakers and scientific advisers. The Evidence Review Report concludes with a summary of the main findings in the form of lessons learned. These findings are specifically structured to address the various policymaking levels, as well as science organisations and institutions.

Chapter 2: Science as a source of advice for policymaking

2.1 THE PURPOSE OF SCIENCE FOR POLICYMAKING

There is no commonly agreed-upon definition of the term 'science' in the literature. The UK Science Council reviewed hundreds of definitions and ended up with a one-sentence characterisation of science:

> *'Science is the pursuit and application of knowledge and understanding of the natural and social world following a systematic methodology based on evidence.'*
>
> (Science Council, 2009)

Even shorter is the definition by the International Network for Government Science Advice (INGSA). Science in their understanding refers to the:

> *'rigorous and methodological study of a subject.'*
>
> (Wilsdon, Allen, & Paulavets, 2014, p. 11)

Most concepts of science also agree that science attempts to produce and test claims about reality. It includes statements that are descriptive (how reality is shaped), analytic (causal and functional relationships between phenomena) and — depending on the specific discipline — normative (how reality should be changed or altered). The overall goal of arriving at a true account of reality remains the essence of scientific enquiry throughout all disciplines (similar attempts in N. R. Campbell, 1921, pp. 27-30).

Scientists utilise their expertise for the purpose of improving the understanding of, or assessing the consequences of, a set of decision options. Alfred Moore (2017) defines expertise 'as the possession of special skill, experience, information or knowledge rooted in the methods, norms, practices and goals of a specific community and which is recognised as legitimate by the wider society' (p. 6). This definition does not make the claim that expertise is based on the assumption of making true statements, but that it gains authority by referring to methodological rules and publicly-accepted authority (p. 59). Using scientific expertise in science and technology studies is not identical, however, with generating scientific statements (Lindblom & Cohen, 1979, p. 7).

In a policy arena, scientific experts are expected to use their skills and knowledge as a means of producing arguments and insights for identifying, selecting and evaluating different courses of collective action. Scientific expertise is used to support policymaking by providing the best available knowledge in understanding a specific problem, generating or creating policy options, evaluating the impacts of different decision options and providing meaning to discourse topics in society (Cairney, 2016; Kenny, Washbourne, Tyler, & Blackstock, 2017). Since such advice includes the prediction of the likely consequences of political actions in the future, experts are also in demand to give advice on how to cope with uncertain events and how to make prudent selections among policy options, even if the policymaker faces uncertain outcomes and heterogeneous preferences (Cadiou, 2001, p. 27). Many policymakers expect scientific experts to help construct strategies that promise to prevent or mitigate negative and promote positive impacts of collective actions. In addition, scientific expertise is demanded as an important input to design and facilitate communication among the different stakeholders in debates, particularly about technology and risk (B. Fischhoff, Brewer, & Downs, 2011).

Science advice has been in high demand in recent times (Gluckman, 2013). This is primarily due to the increased interactions between human interventions and natural responses and, secondarily, to the increased complexity of the knowledge necessary for coping with economic, social, and environmental problems. Population growth, global trade issues, international market structures, transboundary pollution and many other factors of modern life have increased the sensitivity to external disturbances and diminished the capability of social and natural systems to tolerate even small interventions (Wells, 2012).

Although contested by a few (J. L. Simon, 1992), most analysts agree that ecological systems have become more vulnerable as the impact of human intervention has reached and exceeded thresholds of self-repair (Vitousek, Ehrlich, Ehrlich, & Matson, 1986). Furthermore, in a plural social environment, scientific knowledge claims are contested, and policymakers are exposed to a multitude of perspectives, interpretations, and even assertions about factual relationships. Science advice depends on the credibility of the advisory process. Some essential conditions for making advice more effective and convincing are transparency about the underlying assumptions, disclosure of (hidden) interests by those selected to join advisory bodies, sharing common rules of responsibility and accountability, and acknowledging uncertainties and ambiguities when giving advice (Nerlich, Hartley, Raman, & Smith, 2018).

Given this critical situation, what are the potential contributions of expertise to the policy process? In principle, experts can provide knowledge that can help to provide evidence to the policymaking process and improve the quality for generating, selecting, assessing and evaluating policy options (Organisation for Economic Co-operation and Development, 2015). A key term in this respect is *evidence*. Evidence can be defined as a knowledge claim backed up by a recognised scientific procedure or method within the scientific domain for which the claim is made (Cairney, 2016, p. 3; Nutley, Powell, & Davies, 2013). In recent years, the term *evidence-based* policymaking has been advocated as the ideal for prescribing the relationship between science and policymaking (H. T. O. Davies, Nutley, & Mannion, 2000; Nutley et al., 2013). However, many analysts of policy advice have raised doubts about the notion that all policies should be evidence-based (Cairney, 2016; Cartwright & Hardie, 2012):

1. First, scientific advice can be used for policymaking only to the degree that the state-of-the-art in the respective field of knowledge is able to provide reliable information pertaining to the policy options.

2. Second, evidence may be one important component of prudent decision-making but not the only one and, on many issues, not even the decisive one.

3. Third, the evidence may not be conclusive because of uncertainties, ambiguities and limits of understanding.

In view of these arguments, some authors have adopted the language of 'evidence-informed policy' (cf. S. Brown, 2015, p. 5743; Hawkins & Parkhurst, 2016; Oxman, Lavis, Lewin, & Fretheim, 2009; Parkhurst, 2016) to chart a middle-ground position that helps to address some of these challenges, by particularly allowing explicit reflection on the fact that multiple social concerns are relevant to decisions. The SAPEA expert group follows this suggestion. This term 'evidence-informed' assures that all evidence is considered, but not by default used as the single basis for decision-making (Bowen & Zwi, 2005).

At the same time, many policymakers have unrealistic assumptions about scientific advice and the nature of evidence. They may share certain assumptions about expertise that turn out to be wishful thinking or illusions (U. Beck, 1992; Funtowicz & Ravetz, 1990; Jasanoff, 1990, 1991; Parkhurst, 2017, p. 19; Rip, 1982; K. E. Smith, 2013) . Most prominent among them are:

- *Illusion of certainty:* making policymakers more confident about knowing the future than is justified;
- *Illusion of transferability:* making policymakers overconfident that certainty in one aspect of the problem applies to all other aspects as well;
- *Illusion of 'absolute' truth:* making policymakers overconfident with respect to the truthfulness of evidence;
- *Illusion of ubiquitous applicability:* making policymakers overconfident in generalising results from one context to another context;
- *Illusion of a linear relationship between evidence and problem-solving:* making policymakers believe that science can always offer the right solutions to complex problems.

These illusions are often reinforced by the experts themselves. Many experts feel honoured to be asked for advice by powerful agents of society (Renn, 1995). Acting under the expectation of providing unbiased, comprehensive and unambiguous advice, they often fall prey to the temptation to oversell their expertise and provide recommendations far beyond their areas of competence. This overconfidence in one's own expertise gains further momentum if policymakers and advisers share similar values or political orientations. As a result, policymakers and consultants are prone to cultivating these illusions and acting upon them.

In addition to these five types of illusion, experts and policymakers tend to over-emphasise the role of systematic knowledge in decision-making (K. Oliver, Lorenc,

& Innvaer, 2014). As much as political instinct and common sense are poor guides for decision-making without scientific expertise, the belief that scientific knowledge is sufficient to select the correct option is just as shortsighted. Most policy questions involve both systematic as well as experiential and tacit knowledge (Renn, 2010; Wynne, 1989). Systematic knowledge is essential for understanding the impacts of various policy options, and for gaining a better and more comprehensive understanding of the complex relationships between human interventions and their consequences. However, it often provides little insight into designing policies for concrete problems. For example, planning highways, supporting special industries, promoting healthcare for a community and many other issues demand local knowledge on the social context and the specific history of the issue within this context (Jasanoff, 1991; Wynne, 1992b). Only those actors who share common experiences with the issue in question can provide knowledge based on experiential and indigenous perspectives. In essence, scientific, systematic knowledge has its unique and highly valuable place in policy arenas, but making good policy decisions requires more than systematic knowledge and includes different knowledge perspectives from stakeholders, diverse constituencies and affected publics (Smismans 2004).

This is particularly true for so-called *wicked problems*. In 1973, Horst Rittel and Melvin Webber introduced this concept to describe decision and planning situations in which there is neither a common understanding of what the causes for the problem are, nor a clear agreement of the potential solutions to a given problem. The two authors proposed ten important features which characterise wicked problems (Johnston, Rodriguez, Rubenstein, & Swanson, 2019):

1. They do not have a definitive formulation.
2. They do not have a 'stopping rule'. In other words, these problems lack an inherent logic that signals when they are solved.
3. Their solutions are not true or false, only good or bad.
4. There is no way to test the solution to a wicked problem.
5. They cannot be studied through trial and error. Their solutions are irreversible.
6. There is no end to the number of solutions or approaches to a wicked problem.
7. All wicked problems are essentially unique.
8. Wicked problems can always be described as the symptom of other problems.
9. The way a wicked problem is described determines its possible solutions.
10. Planners, that is, those who present solutions to these problems, have no right to be wrong. 'Planners are liable for the consequences of the solutions they generate; the effects can matter a great deal to the people who are touched by those actions'.

Many topics for which science advice is demanded involve wicked problems. They do not allow straightforward articulation, and it is impossible to find effective solutions in a way that they can be derived from linear cause-effect reasoning or ensured over time. The nature of wicked and/or complex problems is that there will be no 'magic bullet' to solve them, but that a better understanding and a more effective procedure for processing them will emerge, which can only help to facilitate policymaking, even if only limited answers are provided (B. G. Peters, 2017, p. 395). In Chapter 5, the SAPEA expert group will revisit the topic of wicked problems and provide evidence and experience of how to deal with wicked problems in the context of scientific advice for policymaking.

2.2 THE RELEVANCE OF SCIENTIFIC EXPERTISE FOR POLICYMAKING

There is little debate in the literature that the inclusion of external expertise is essential as a major resource for designing and legitimising public policies (Jasanoff, 1990; National Research Council, 2012; Organisation for Economic Co-operation and Development, 2017). A major debate has evolved, however, on the status of scientific expertise for representing all or most of the relevant knowledge that is included in these policies. This debate includes two related controversies: the first controversy deals with the problem of objectivity and realism; the second one with the role of other forms of knowledge that 'non-experts' have accumulated over time.

This is not the place to review these two controversies in detail (see Bradbury, 1989; Cairney, 2016; Parkhurst, 2017; Shrader-Frechette, 1991; van der Sluijs, Petersen, Janssen, Risbey, & Ravetz, 2008). There is agreement, however, among all camps in this debate that systematic knowledge is instrumental to understanding phenomena and providing insights that help to understand and tackle problems. Most analysts also agree that systematic knowledge should be generated and evaluated according to the established rules or conventions of the respective discipline (Jäger, 1998, p. 145; Lentsch & Weingart, 2011b). Methodological rigour that seeks to attain valid, reliable and robust evidence remains the most important yardstick for judging the quality of scientific insights. Those scholars who support the notion of social constructivism of science do not question the importance of methodological rules, but are sceptical about whether the results of scientific enquiries represent objective or even unambiguous descriptions of reality (Knorr-Cetina, 1981; Latour & Woolgar, 1979). The advocates of a realist perspective on science do not object to the insight that science represents a social and potentially flawed activity to produce and test truth claims, but believe that the review process in scientific communities ensures a step-by-step approximation to the true state of the world (Popper & Notturno, 1994).

For the analysis of scientific input to policymaking, the divide between the constructivists and the realists (and all the positions in-between) is less of a problem than many advocates of each side claim (Harding, 1992; Jasanoff, 2004b; Wagenaar, 2014). A discourse on what constitutes robust knowledge deals with different, sometimes competing claims that obtain validity only through a compatibility check with acknowledged procedures of data collection and interpretation, a proof of theoretical compatibility and conclusiveness, and the provision of inter-subjective opportunities for reproduction (Shrader-Frechette, 1991, p. 46). Obviously, many research results do not reach the maturity of proven facts, but even intermediary products of knowledge, ranging from plain hypotheses via plausible deductions to empirically proven relationships, strive for further perfection (cf. the pedigree scheme of Funtowicz & Ravetz, 1990). On the other hand, even the most ardent proponent of a realist perspective will admit that only intermediary types of knowledge are often available when it comes to assessing and evaluating complex phenomena (Cilliers, 2005). Furthermore, policies address different constituencies, and these constituencies have distinct expectations of what these policies should entail. As Wagenaar states (2014, p. 20): 'Reconstructing the subjective meaning that a particular policy has for its target audience, thereby revealing the practical and conceptual limitations of the policy, is an important task of interpretive policy analysis'. What does this mean for the status and function of scientific expertise in policy contexts?

1. First, scientific input has become a major component of collective decision-making in all domains of economics, politics and societal affairs. The degree to which the results of scientific enquiry are taken as the ultimate benchmark to judge the appropriateness and validity of competing knowledge claims is contested in the literature and contested among policymakers and different social groups. Frequently, the status of scientific evidence becomes one of the discussion points during social or political deliberation, depending on the context and the maturity of scientific knowledge in the respective policy arenas (Cartwright & Hardie, 2012). For example, if the issue is the effect of a specific toxic substance on human health, observations by the affected groups may serve as heuristic tools for further enquiry, but there is still a significant — and indeed, essential — role for toxicological and epidemiological investigations. If the issue is siting of an incinerator, local knowledge about sensitive ecosystems or traffic flows may be more relevant than systematic knowledge about these impacts in general (a good example of the relevance of 'societal' knowledge can be found in Wynne (1989)).

2. Second, the resolution of competing claims of scientific knowledge is usually governed by the established rules within the respective discipline. These rules may not be perfect, and even contested within the community, yet they are regarded as superior to any other alternative, in particular, intuition (Shrader-Frechette, 1991, p. 190).

3. Third, many policy options require systematic knowledge that is not available, or still in its infancy, or in an intermediary state. Analytic procedures are then demanded by policymakers, as a means to assess the state-of-the-art in scientific knowledge. There may be neither a complete understanding of the phenomenon, nor a clear causal relationship, but valuable educated guesses by experts. These need to be labelled as such (Gerken, 2018). Furthermore, it is essential to demarcate the limits of 'reasonable' claims, i.e. identify the range of those claims that are still compatible with the state-of-the-art in a specific knowledge domain (Parkhurst & Abeysinghe, 2016).

4. Fourth, knowledge claims can be systematic and valid across contexts as well as case-specific and context-dependent. Both forms of knowledge have a legitimate place in science-informed decision-making. How they are used depends on the context and the type of knowledge required for the issue in question (Nutley, Walter, & Davies, 2007; Wynne, 1992b).

All four points show the importance of scientific evidence for policy- and decision-making but also make clear that choosing the appropriate policy options requires more than looking at the scientific evidence alone. In essence, science provides a source for robust and reliable knowledge that is based on a systematic search for evidence and rigorous use of methodological rules. Knowledge claims derived from scientific activities often represent the best available systematic knowledge for a given subject, but it is not the only relevant or necessary knowledge that decision-makers use or even should use. This is partially due to the policymaking context and to the nature of knowledge as complex, uncertain and ambiguous. The last point will be taken up in the next section.

2.3 COMPLEXITY, UNCERTAINTY AND AMBIGUITY: THREE CONDITIONS OF SCIENTIFIC KNOWLEDGE

2.3.1 Complexity

There are different concepts of complexity in the scientific literature. The classic definition stems from Axelrod and Cohen (2000, p. 7):

> *'[a] system is complex when there are strong interactions among its elements, so that current events heavily influence the probabilities of many kinds of later events'.*

A core aspect of complexity is the density of the interactions in a system — more so than the number of its parts (Wagenaar, 2007). A more causal understanding of complexity highlights the difficulty of identifying and quantifying links between a multitude of interdependent variables under conditions of time dependencies and feedback loops (cf. Cairney, 2012; Underdal, 2010). A crucial aspect in this respect concerns the applicability of statistical methods or models to make inferences or predictions, based on the given dataset. If the chain of events between a cause and an effect follows a linear relationship (as, for example, in mechanical systems or many thermodynamic relationships), statistical models and experimental designs are sufficient to substantiate a causal knowledge claim. Such simple relationships may still be associated with high uncertainty, for example, if only few data are available or the effect is stochastic by its nature.

Sophisticated models of probabilistic inferences are required if the relationship between cause and effects becomes more complex (Lucas, Renn, & Jaeger, 2018; Sanderson, 2009). The nature of this difficulty may be traced back to interactive effects among these candidates (synergisms and antagonisms, positive and negative feedback loops), long delay periods between cause and effect, inter-individual variation, intervening variables, and others (Chu, Strand, & Fjelland, 2003). It is precisely these complexities that make sophisticated scientific investigations necessary, since the cause–effect or sequential relationship is neither obvious, nor directly observable.

Non-linear response functions may also result from feedback loops that constitute a complex web of intervening variables. Complexity therefore requires sensitivity to non-linear transitions, as well as to scale (on different levels). It also requires that we take into account a multitude of cause-effect pathways and consider the often difficult-to-draw distinction between effect and noise (Poli, 2013). Examples of highly complex phenomena include climate change, interactions between human interventions and natural dynamics, multi-actor, multi-pathway social interactions, economic perturbations, failures of large interconnected infrastructures and risks of critical loads to sensitive ecosystems. Complexity is a major impediment to providing reliable insights about the likely consequences of decision options. They are often difficult or impossible to predict with any degree of reliability and they often underestimate causal chains that start with small, even unlikely events and proliferate through the entire system.

How does complexity affect the interaction between scientific experts and policymakers? The most important aspect is the emphasis on relationships between interconnected phenomena in dynamic interactions. Wagenaar (2007) suggests using the following characteristics to improve policymakers' understanding of complexity:

- Complex systems need a holistic perspective, if one strives to understand their dynamics and implications for policies. This implies that disciplinary knowledge may miss the main characteristics of a complex system; interdisciplinary and even transdisciplinary knowledge is better suited to coping with complex relationships.
- The transition in complex systems is not necessarily continuous, but can be abrupt. Tipping points may be reached that induce rapid changes and transitions from equilibria.
- Complex systems have indeterminate outcomes. There is rarely the one best solution to a problem, but a whole set of potentially useful strategies that need to be carefully designed and monitored.
- Complex systems are characterised by historicity; they have a past and a future. Knowledge on such systems is always embedded in a spatial and time-dependent context. Policy options that emphasise adaptive behavior and continuous learning are more effective in dealing with complex problems, than detailed plans of what to do within a given time frame.

This list is echoed by many other analysts of complexity. For dealing with complex relationships between the natural environment and human interventions, Preiser et al. (2018) came up with six major principles for studying complex systems that are particularly relevant for policymaking. These are:

1. Principle 1: Complex adaptive social-ecological systems (CAS) are constituted relationally
2. Principle 2: CAS have adaptive capacities
3. Principle 3: Dynamic processes generate CAS behaviour
4. Principle 4: CAS are radically open
5. Principle 5: CAS are contextually determined
6. Principle 6: Novel qualities emerge through complex causality

As the authors point out, these characteristics have a direct impact on how scientific advice differs from the traditional linear model of providing decision-makers with the likely impacts of various decision options and letting them decide which of the options, and their likely impacts, are most desirable from a value perspective. Rather, the advice provides better insights into a more complete understanding of, and sensitivity towards, the many (often non-linear) relationships between the various drivers and effects of human interventions into nature and society (see also Juarrero, 2002). Policymaking becomes (or should become) more alert to the many impacts that actions can trigger in a complex system, without ever being complete or fully cognisant. Furthermore, as pointed out in Chapter 4, a problem is not defined by objective circumstances or forces, but by the various frames that observers of the problem associate with the system (Cilliers, 2002; De Martino, Kumaran, Seymour, & Dolan, 2006). This dependence on the observer should not be mistaken for scientific relativism; it is rather an act of defining boundaries of what is included and excluded, and finding the best evidence within the system that promises to demonstrate the effects that policymakers intend to achieve (Rika Preiser & Cilliers, 2010; Woermann & Cilliers, 2012).

The need to address and integrate various frames for a better understanding of complex systems has also been highlighted by Cairney (2016), who advocates a joint search for appropriate knowledge that is adjusted to the special circumstances and action possibilities within a policy framework. Ansell and Geyer (2017) advocate a pragmatic handling of complexity in policymaking contexts. Taking the example of drug regulations, they show the importance of visual illustrations of complex relationships and multi-dimensional scoring. Finally, complex science theorists support the notion of integrating different forms of knowledge into the policy process, as a variety of perspectives and viewpoints provide a more comprehensive representation of the situational constraints and choices (Folke, Biggs, Norström, Reyers, & Rockström, 2016). As explained later in Section 4.2, high complexity confines scientific input to policymaking to the function of enlightenment and orientation, but is often unable to provide strategies or impact assessments.

Science is not always able to recommend clear guidelines, and policy advice does not always provide clear solutions, in particular, in situations involving complex systems that require interdisciplinary approaches. Policymakers often also need to make decisions in situations where they are subject to multiple, often competing, influences and concerns and where science advice may be compromised in favour of values (Parkhurst, 2017; Pielke, 2007).

2.3.2 Scientific uncertainty

English dictionary definitions of 'uncertainty' are generally framed rather broadly, e.g. 'the state of being uncertain' where 'uncertain' is defined as 'not able to be relied on; not known or definite' ("Oxford Dictionaries," 2018). Many technical definitions are also broadly framed; e.g. the US National Research Council's Committee on Improving Risk Analysis Approaches defined uncertainty as 'lack or incompleteness of information' (National Research Council, 2009).

In a much earlier definition, the economist Frank Knight restricted the term 'uncertainty' to unquantifiable uncertainty, distinguishing it from 'risk', which he used for quantifiable uncertainty, where the distribution of outcomes is known from *a priori* calculations or statistical data (Knight, 1921). This 'Knightian' view of uncertainty is common in economics (e.g. N. Stern, 2008) and in some perspectives on approaches to scientific advice (e.g. Stirling, 2010). However, as Cooke (2015) points out, Knight recognised that 'we can also employ the terms 'objective' and 'subjective' probability to designate the risk and uncertainty respectively' (Knight, 1921, part III, chapter VIII). Knight also recognised that, in practice, people often use *probability* to express the types of uncertainty he would regard as unquantifiable, and he went so far as to state that forming good judgements of this type is the principal skill that makes a person 'serviceable' in business (Knight, 1921, part III, chapter VII). Similarly, it may be assumed, advice is requested from scientists because they are thought able to provide useful judgements in their field of expertise.

The work of Ramsey (1926), de Finetti (1937), Savage (1954) and others has since established an operational and theoretical framework for subjective probability, which justifies its use in probability calculations on the same basis as 'objective' probabilities derived from frequency data. Within that framework, all forms of uncertainty may be quantified using subjective probability, even for complex problems, provided that the question under assessment is well-defined (i.e. refers to the occurrence or non-occurrence of an unambiguously specified event). Both the Knightian and Bayesian perspectives are, for example, taken into account in the European Food Safety Authority's guidance on uncertainty analysis in scientific assessment, which defines uncertainty as 'a general term referring to all types of limitations in available knowledge that affect the range and probability of possible answers to an assessment question', but also emphasises the need to identify situations where probabilities cannot be given (European Food Safety Authority, 2018b, 2018c) .

Scientific uncertainty relates to the limitedness or even absence of scientific knowledge (data, information) that makes it difficult to assess exactly the probability or likelihood and the range and intensity of possible outcomes (cf. Filar & Haurie, 2010). Uncertainty most often results from an incomplete or inadequate reduction of complexity in modelling cause-effect chains (cf. Marti, Ermoliev, & Makowski, 2010). Whether the world is inherently uncertain is a philosophical question that is not pursued here (Aven & Renn, 2009). It is essential to acknowledge (cf. Chapter 3) that human knowledge is always incomplete and selective, and thus contingent upon uncertain assumptions, assertions and predictions (Funtowicz & Ravetz, 1992; Laudan, 1996; Renn, 2008, p. 75). It is obvious that the modelled probability distributions within a numerical relational system can only represent an approximation of the empirical relational system that helps elucidate and predict uncertain events. It therefore seems prudent to include additional aspects of uncertainty when making claims of causal relationships (van Asselt, 2000, pp. 93-138; 2005). Although there is no consensus in the literature on the best means of disaggregating uncertainties, the following categories appear to be an appropriate means of distinguishing between the key components of uncertainty (Renn, Klinke, & Van Asselt, 2011):

- *Variability* refers to the different vulnerability of targets, such as the divergence of individual responses to identical stimuli among individual targets within a relevant population such as humans, animals, plants, landscapes, etc.;
- *Inferential effects* relate to systematic and random errors in modelling, including problems of extrapolating or deducing inferences from small statistical samples, using analogies to frame research questions and data acquisition, and using scientific conventions to determine what is regarded as sufficient proof (such as 95% interval of a normal distribution function). Some of these uncertainties can be expressed through statistical confidence intervals, while others rely on expert judgements;
- *Indeterminacy* results from a genuine stochastic relationship between cause and effects, apparently non-causal or non-cyclical random events, or badly understood non-linear, chaotic relationships;
- *System boundaries* allude to uncertainties stemming from restricted models and the need to focus on a limited number of variables and parameters;
- *Ignorance* means the lack of knowledge about the probability of occurrence of a damaging event and about its possible consequences.

The first two components of uncertainty qualify as statistically quantifiable uncertainty and, therefore, can be reduced by improving existing knowledge, applying standard statistical instruments such as Monte Carlo simulation and estimating random errors within an empirically proven distribution. The last three components represent genuine uncertainty and can be characterised, to some extent, by using scientific approaches, but cannot be completely resolved. The validity of the end results is questionable and, for making prudent policy decisions, additional information is needed, such as subjective probabilities and/or confidence levels for scientific conclusions or estimates, potential alternative pathways of cause–effect relationships, ranges of reasonable estimates, maximum loss scenarios and others (e.g. Stirling, 2008). Furthermore, beyond the five components, representing absence or lack of knowledge as well as natural variability and indeterminacy (often under the heading of epistemic and aleatory uncertainties), other policy-related uncertainty types need to be considered (International Risk Governance Council, 2015). These include:

- Expert subjectivity, which may be due to philosophical or professional orientation, and conflict of interest (or even fraud) (see also Section 4.3);
- Communication uncertainty, which may be associated with ambiguity (lack of clarity about the intended meaning of a term or a concept), context dependence (failure to specify the context), under-specificity (overly-general statements), and vagueness;
- Under-determination of theory by data, where evidence available to scientists is not sufficient for forming a coherent theory or choosing between alternative theories supported by the data.

Examples of high uncertainty include:

- Many natural disasters, such as earthquakes;
- Environmental impacts, such as the cumulative effects of various environmental hazards below the threshold of statistical significance, or gradual degradation of eco-services due to the loss of biological diversity;
- Socio-political consequences, such as the persistence of political stability;
- Economic reactions to policy changes, for example, on the stock market;
- Regional impacts due to global climate change;
- The occurrence of pandemics (such as SARS or avian flu), caused by viruses characterised by a rapid rate of mutation.

There are other ways to classify and categorise uncertainty. Funtowicz and Ravetz (1990) distinguished between technical (inexactness), methodological (unreliability) and epistemological ((ignorance) dimensions of uncertainty. Building on that typology, Van der Sluijs (2017) proposed to add the societal dimension (limited social robustness). Table 1 below gives examples of the various sources of uncertainty for each dimension.

Dimension	Type	Can stem from or can be produced by
Technical	Inexactness	*Intrinsic uncertainty:* variability; stochasticity; heterogeneity *Technical limitations:* error bars, ranges, variance; resolution error (spatial, temporal); aggregation error; linguistic imprecision, unclear definitions
Methodological	Unreliability	*Limited internal strength of the knowledge base in*: use of proxies; empirical basis; theoretical understanding; methodological rigour (including management of anomalies); validation
Epistemological	Ignorance	*Limited theoretical understanding* *System indeterminacy*: open-endedness of system under study; chaotic behaviour *Intrinsic unknowability with active ignorance*: model fixes for reasons understood; limited domain of validity of assumptions; limited domains of applicability of functional relations; numerical error; surprises type A (some awareness of possibility exists) *Intrinsic unknowability with passive ignorance*: bugs (software error, hardware error, typos); model fixes for reasons not understood; surprises type B (no awareness of possibility)
Societal	Limited social robustness	*Limited external strength of the knowledge base in*: completeness of set of relevant aspects; exploration of rival problem framings; management of dissent; extended peer acceptance/stakeholder involvement; transparency; accessibility *Bias/value ladenness:* value laden assumptions; motivational bias (interests, incentives); disciplinary bias; cultural bias; choice of (modelling) approach (e.g. bottom up, top down); subjective judgement

Table 1. Dimensions of uncertainty (van der Sluijs, 2017).

According to Maxim and van der Sluijs (2011), uncertainty sources affecting knowledge production processes can be further distinguished according to location, type and position within the knowledge generation cycle:

- 'Content uncertainty' is related to data selection and curation, models' construction and quality assurance, and statistical procedures. It also includes conceptual uncertainty, understood as ignorance about qualitative relationships between phenomena;
- 'Context uncertainty' relates to the socio-economic and political factors influencing the knowledge production process. Context means identifying the boundaries of the real world to be modelled at the moment that the problem is framed;

- 'Procedural uncertainty' relates to the procedural quality of the process of knowledge construction. Under this domain fall considerations of completeness, credibility, transparency, saliency, credibility, legitimacy, and fairness.

The relative impact of content, contextual and procedural uncertainty is highly dependent on the location in the knowledge cycle: 'problem framing', 'knowledge production', and 'knowledge communication and use' all have their distinctive characteristics. The concept of quality as applied to scientific evidence is not the same as quality in the deployment of the evidence for policy. For example, excellent scientific quality may simply escape, be ignored, or be miscommunicated accidentally or instrumentally, with a resulting poor policy decision, while — at the opposite extreme — modest scientific quality may end up being sufficient for the purpose of reaching a desirable policy compromise (Wynne & Dressel, 2001). The interplay between content, procedural, and contextual uncertainties may produce unforeseen effects (Maxim & van der Sluijs, 2011). For example, in a regulatory context, regulators may impose the use of risk assessment methods that are inadequate for the nature of the risk, or the experts involved may lack the relevant competence or enough time to critically review the knowledge.

2.3.3 Socio-political ambiguity

While more and better data and information may reduce scientific uncertainty, more knowledge does not necessarily reduce ambiguity. Ambiguity thus indicates a situation of ambivalence in which different, and sometimes divergent, streams of thinking and interpretation about the same risk phenomena and their circumstances are apparent (cf. Feldman, 1989; Zahariadis, 2003). It is prudent to distinguish between interpretative and normative ambiguity, which both relate to divergent or contested perspectives on the justification or severity of a given threat, or wider 'meanings' associated with it (Renn, 2008, p. 77; Stirling, 2003).

Interpretative ambiguity denotes the variability of (legitimate) interpretations, based on identical observations or data assessment results, e.g. an adverse or non-adverse effect (Wagenaar, 2014). Variability of interpretation, however, is not restricted to expert dissent. It is also a common characteristic of policymakers, social interest groups and affected communities. They each may have their 'own' interpretation of the scientific results (Horlick-Jones & Sime, 2004). Moreover, in contemporary pluralist societies, diversity of risk perspectives within and between social groups is generally fostered by divergent value preferences, variations in interests and very few, if any, universally applicable moral principles; all the more so, if the problems addressed are complex and uncertain (Hammond, 2005; Mitchell, 2004). Examples for high interpretative ambiguity include the effects of low dose non-ionising radiation, low concentrations of genotoxic substances, or the impacts of alien species to natural environments (e.g. how far does one go back in time when determining which species is alien and which is domestic?).

A second variant of ambiguity refers to **normative ambiguity**. This alludes to different concepts of what can be regarded as desirable or permissible, referring for example to ethics, quality of life parameters, distribution of risks and benefits, etc. A condition of ambiguity emerges where the problem lies in agreeing on the appropriate values, priorities, assumptions, or boundaries to be applied to the definition of possible outcomes (Renn et al., 2011). Normative ambiguities can be associated, for example, with exposure to noise, aquaculture in sensitive areas, pre-natal genetic screening and effects of smoking and drinking. In these cases, science is very familiar with the impacts of the various triggers and there is little uncertainty and interpretative ambiguity about cause-effect relationships. Yet there is considerable debate about whether the application is tolerable or not (Bandle, 2007).

Many problems are characterised by a mixture of complexity, uncertainty and ambiguity. Passive smoking may be a good example of low complexity and uncertainty, but high ambiguity. Many nations still face a debate on whether smoking should be allowed and where it should be restricted. Therapeutic cloning may be a good candidate for high complexity and high ambiguity, but relatively little uncertainty. The impacts are well known and represented by scientific models, yet the moral and ethical acceptability is fiercely debated. The massive emission of aerosols into the atmosphere to combat the effects of greenhouse gases (geoengineering) might be cited as an example for high complexity, uncertainty and ambiguity.

Interpretative and normative ambiguity are also often labelled as controversial or contested evidence (Parkhurst, 2016). However, even if there are differences in interpretation or normative implications, they are not necessarily adversarial or even polarised. Different perspectives on the same evidence could also lead to a more comprehensive, complementary and inclusive understanding of the issue in question. That is why the term ‘ambiguity’ has been chosen to represent the plurality of scientifically justifiable viewpoints on the meaning and implications of scientific evidence (Renn et al., 2011).

Chapter 3: What can science offer to policymaking?
The potential contribution of science, evidence and knowledge

3.1 SCIENCE ADVICE IN CONTEMPORARY SOCIETIES

Scientific knowledge and expertise are more important than ever in today's society. Scientific advice to policymakers and politicians aims to provide a crucial evidence-based input to policies and policy-related decisions. Policymakers need guidance to help achieve social goals, and also require information about the possible risks and consequences of decisions, including potential side-effects, costs, likely impacts, public perceptions and matters of environmental sustainability (U. Beck, 1992; Felt et al., 2013; Jasanoff, 2005a). In the context of reason-based policy and action, there is therefore a clear requirement for robust evidence to be at the core of decision-making. Science can ensure that a solid base of knowledge is provided for societal debate and, in cases when this is not possible, science can at least help clarify the factual basis of knowledge claims and the values at stake. However, there are also large institutional and societal pressures on science and scientists, not least in terms of the challenges associated with different sources of scientific funding, apparent public scepticism about the nature of 'expert' knowledge claims, and the changing demands on early-career researchers (Felt et al., 2013; Fochler & de Rijcke, 2017; Greenberg, 2007; Jasanoff & Simmet, 2017; Sismondo, 2017).

The large body of literature and evidence in this field extends beyond the potential benefits of science, in order to consider the uses of scientific information in practice — and also the borderline between robust scientific evidence and legitimate matters of societal choice, ethics, policy and politics. Scientific knowledge in this setting must particularly deal with questions of social and technical complexity, as well as uncertainty and ambiguity (see Chapter 2). It needs to operate in situations where multi-disciplinarity is a prerequisite. There are also important questions around the framing and definition of the problem for which a scientific answer is sought (Gieryn, 1999). All this, in turn, raises questions of the ethical, epistemological and evidential quality dimensions of scientific evidence within sometimes-heated contexts (Ezrahi, 1990; Felt et al., 2007; Sundqvist, Bohlin, Hermansen, & Yearley, 2015; Wynne, 2001).

This chapter reviews the potential contribution that scientific advice can make to policymaking. Drawing upon a substantial body of scholarship and previous experience, the intention is to highlight both the role that science can play in informing policy, but also the many questions — and possible criticisms — that scientific advice can face once it moves into this domain. Whilst science has much to offer both specific policy decisions and the broader direction of public policies, it is by no means certain that it can always fulfil this role. As the evidence base strongly suggests, the provision of scientific advice raises more challenging questions than is indicated by the conventional notion of simply 'speaking truth to power' (Jasanoff, 1990; Macnaghten & Chilvers, 2014; Stilgoe, Alan Irwin, & Jones, 2006).

The chapter first considers the nature of science and scientific advice. It then addresses issues of the scientific and ethical responsibilities of scientific advisers. After this, the sub-sections that follow focus on scientific dissent, uncertainty and ignorance.

3.2 CONDITIONS: SCIENCE AS A FORM OF KNOWLEDGE

Scientific knowledge is acquired by exposing ideas and hypotheses to systematic and well-documented procedures, such as testing and analysis of carefully-controlled experimental data, stringent argumentation and scholarship, and the collection of empirical data through quantitative and qualitative methods (cf. Duschl, 2007). Scientific knowledge is a source of evidence and advice that can play an important role in the formulation and development of policy and decision-making, from short-term emergencies to long-term global challenges. In this context, good science communication promotes critique and self-correction, acknowledges the limits of data and methods, and faithfully accounts for the sources of evidence (S. R. Davies & Horst, 2016; Alan Irwin, Bucchi, Felt, Smallman, & Yearley, 2018). To be used as a basis for advice, evidence has to include not only scientific insights, uncertainties and ambiguities, but also causal relationships and explanations, as well as other supporting factors. Scientific advice must then be based on the best available evidence and communicated in a transparent and accountable way, explicitly and honestly assessing and conveying uncertainties and tensions.

As already noted, in this evidence review, a broad rather than a narrow definition of what science means is taken, i.e. a view of 'science' as embracing not only the natural sciences, but also the humanities and social sciences. These various intellectual traditions are guided by different criteria of what science means, and how scientific claims are to be tested and validated. A requirement of this understanding of science is that knowledge claims are described in such a way that the procedures to accomplish the results can be independently reproduced, and the results of scientific enquiries subjected to external review in order to assess their validity. Peer review and reproducibility are the hallmarks of science to withstand tests in order to reduce the risk of inaccurate conclusions or, in some rare cases, fraudulent data (Fanelli, 2018).

For much of the twentieth century, the distinction between 'good' and 'bad' science was drawn along the much discussed, but highly divisive, language of demarcating between science and pseudo-science (Hansson, 2017). Scientific theories, according to the falsificationist approach advocated by Karl Popper (Popper, 1959) were, in principle, open to falsification, whilst pseudo-scientific theories, although adopting the apparatus of scientific methodology (for instance, by talking about theories and hypothesis), were not abandoned, but merely modified or adjusted, even when faced with evidence to the contrary. For Popper, the most noteworthy examples of such pseudo-science were Marxism and psychoanalysis (Grünbaum, 1979). The Popperian approach to the question of demarcation is still popular among some natural scientists but is rejected by most philosophers of science. They do not find the strong distinction between falsifiable and unfalsifiable theories very useful. They point out that no scientific theory is ever deemed to be false, just because of a mismatch between a theory and observation or experiment that goes against it. Instead, the picture is more complex. When scientific theories are deemed as falsified as a body, one can always save a particular scientific theory by making adjustments within the theory to accommodate any recalcitrant experience against some subset of the theory (Lakatos, 1970).

Many contemporary scientists and philosophers of science see reproducibility/replicability as the main criterion for good science; the idea here is that the results of good, in the sense of reliable science, should be open to replication. Hence the talk of the crisis of replicability in some areas of science, which has been a cause for concern, particularly in medicine, economics and psychology, but also other sciences. However, even this criterion is not free of problems. Some events in the natural world are unique. They may occur only once or extremely rarely. Devising scientific experiments that are suitable for replication is often difficult, if not impossible, to achieve. The theory of evolution gives us a good example of scientific theory devised to explain a non-repeatable event.

A heuristic for distinguishing good from bad science at a very basic level, common to both the natural and social sciences, is the reliance on the mechanism of peer review. However, peer review is a reliable measure of quality and method of control only insofar as the reviewers are reliable, attentive and well-informed. As the above considerations in ensuring a sound peer reviews imply, it is almost a truism to say that good science is reliable; it is fruitful insofar as it produces new knowledge and, at least, when it comes to the intersection between science and policy, good science is also practically useful science (Hansson, 2007; Rubinstein, 2006). Beyond this truism, it may be easier to outline the criteria for what makes for 'bad science'. A number of practices are frequently signalled as markers of 'bad science' and they include (Hansson, 2013, pp. 70-71):

- *Belief in authority*: It is contended that some person or persons have a special ability to determine what is true or false. Others have to accept their judgements.
- *Unrepeatable experiments*: Reliance is put on experiments that cannot be repeated by others with the same outcome.
- *Handpicked examples*: Handpicked examples are used, although they are not representative of the general category that the investigation refers to.
- *Unwillingness to test*: A theory is not tested, although it is possible to test it.
- *Disregard of refuting information*: Observations or experiments that conflict with a theory are neglected.
- *Built-in subterfuge*: The testing of a theory is so arranged that the theory can only be confirmed, never disconfirmed, by the outcome.

- *Explanations are abandoned without replacement*. Tenable explanations are given up without being replaced, so that the new theory leaves much more unexplained than the previous one.

Such science, it is assumed, in the long run at least, will not lead to fruitful discoveries and new knowledge. It is more difficult to come up with a positive list of what constitutes good science. Yet, most analysts agree that it is the process of *doing* science that demarcates good from bad science rather than properties of the resulting products.

Well-established hypotheses may lead to new theories, which have to withstand tests for long periods of time (Niiniluoto, 1984; Sarton, 1936). No theory can, however, be regarded as final. As new information and new observations appear which may be in conflict with the theory, refinement, modification or even rejection of the theory may be required (European Food Safety Authority, 2018a). Only a theory which has withstood tests for a long period of time, and under various conditions, can be regarded as solid.

There are, as mentioned above, various traditions of what is meant by science and scientific enquiry — even if there are also shared strands across this diversity. Thus, work within Science and Technology Studies (STS) has emphasised the social and epistemological processes underlying the development of scientific knowledge claims, often drawing attention to the specific contexts and conditions within which 'facts' are developed (Collins & Pinch, 1993; Latour, 1987; Latour & Woolgar, 1979). Also from this perspective, scientific advice must often operate in conditions of social as well as scientific uncertainty; the 'boundary' between science and non-science can, in practice, be problematic to establish (Gieryn, 1983; Alan Irwin, 2008; Nelkin, 1975). However, for many scholars within this tradition, the point is not simply to 'deconstruct' scientific knowledge claims, but rather to explore in close empirical terms the manner in which such claims are developed, defended and built upon (Gieryn, 1999; Jasanoff, 1999). Scientific advice does not simply 'shine brightly' on the policy process but must be legitimised, supported and communicated within specific social and institutional processes (Jasanoff, 2004c; Nowotny, 2007).

If 'science' includes also the social sciences and humanities, quantitative empirical data are often neither available, nor of great relevance to the type of questions or phenomena being addressed. Knowledge claims in these sciences are subject to other forms of tests and scrutiny that are mainly derived from hermeneutic practices. Logical reasoning, making sense of individual, group or cultural expressions and behavioural responses, as well as providing meaning to historical events by comparing and analysing documents, are some of the common procedures to assure scientific quality and validity. Of course, logical reasoning is not only the preserve of the humanities and behavioural science but is a characteristic of scientific knowledge production more broadly.

Notions of evidence, hypothesis-testing and proof vary across scientific fields (and even within the social sciences, for example, where there are different quantitative and qualitative traditions, each with its own approach to assessing scientific quality). It is also the case that the object of study will inevitably affect the kinds of scientific evidence that may be brought forward (for obvious ethical reasons but also due to more epistemological factors, such as the capacity of human agents to subvert, respond to and challenge apparently 'objective' statements and externally-controlled conditions (Giddens, 1984)).

Different procedures for policy advice have been developed, including systematic reviews building on detailed and careful collection of evidence to answer a well-defined question and meta-analyses using statistics to combine data from multiple separate studies. Evidence hierarchies have been found useful for sorting out irrelevant evidence, but have also been criticised for missing useful evidence (Nutley et al., 2013; Parkhurst, 2017).

Science is often asked to provide impartial and reliable knowledge. However, scientific results are not always reliable, and advisers may be biased (Fanelli, Costas, & Ioannidis, 2017) or searching for a particular outcome, e.g. as a result of being sponsored by a stakeholder within a policy domain (Bok, 2003; Greenberg, 2007). While there has been debate over the issue of reproducibility in science, there is also substantial evidence to suggest that talk of a 'crisis' in this respect is greatly exaggerated (Fanelli, 2018; O. H. Petersen, 2019).

Scientists are citizens with different ideologies, who may not be able to completely exclude their own convictions from their research, leading to biased observations and biased interpretations. Advisers may have personal interests, and therefore not tell all aspects of the current 'truth'. Lack of knowledge, selective presentation of information and use of statistics in a biased way are other sources of unreliable advice (Fischer, 1990; Greenberg, 2001; Guston, 2000; Sarewitz, 1996). Furthermore, unintended negative or harmful consequences may be considered irrelevant by the adviser. Scientists may also use their authority to provide opinions on issues that fall outside the scope of their expertise, and policy advisers are not always accountable for the integrity of their advice (Renn, 2001). Non-rigorous, badly-designed scientific studies by advisers who are not qualified and who have their own agenda, may lead to declining confidence in science. It should be emphasised that these can be subtle processes, as well as matters of deliberately 'false' or 'fake' advice. As cases such as the handling of BSE in the United Kingdom suggest, scientific advisers may act with good intentions but nevertheless fail to deal adequately with scientific and social uncertainties, especially when operating within 'closed' and non-transparent policy systems (Horlick-Jones, Walls, et al., 2007; Jones, 2001; Phillips, Bridgeman, & Ferguson-Smith, 2000).

There can also be more or less accurate uses of scientific evidence by policymakers. Political interests may drive the misuse or manipulation of evidence. Policymakers may not always be transparent with what they take for granted and where they are open to new insights. They may ignore scientific facts which are not in line with their ideology and only accept reports that suit their own agenda. Evidence can be manipulated and not presented faithfully in order to serve political goals, and pieces of specific evidence can be cherry-picked (All European Academies, 2017; Parkhurst, 2017). The temptation to deliver simple messages and a picture of consensus may be strong (as also evidenced by the UK BSE case (Alan Irwin, 2014)). However, policymakers also need to look beyond science. Political decisions are always a combination of assessing the consequences of each decision option and judging their respective desirability, on the basis of values, preferences and political programmes. They cannot be based solely on scientific evidence (Collingridge & Reeve, 1986; Wildavsky, 1987). Additional concerns based on values need to be taken into account. The choice between different competing social values may even be more important than 'technical' details about likely consequences of decision options (Fischer, 2000). Social interests may be less transparent but science advisers need to admit that other sorts of analyses, and other sorts of perspective, must also inform political decisions (Epstein, 1996; Alan Irwin, 1995; Yearley, 1992).

An expert needs to understand that there are many different fields of knowledge and practices within the science domain as well as outside, and that these fields and practices are sometimes in conflict with one another. In such cases, fair political decisions are required, in spite of uncertainty and ambiguity (R. Löfstedt & Bouder, 2017). Scientists can certainly be helpful in this regard, but they cannot and should not make the final decisions.

3.3 SCIENTIFIC EVIDENCE: WHAT CONSTITUTES 'GOOD' EVIDENCE

There is no simple answer to the question of what characterises good evidence, as it varies with the question and the framing of the problem. It depends on what we want to know, for what purposes, and to what context the scientific advice is being addressed. Advisers need to define the sources for their advice and the limits to the validity of those sources (Cartwright & Hardie, 2012), and to declare different views, if there are legitimate (methodologically defensible) differences within the respective scientific communities. Audited standards to grade studies have been requested (I. Boyd, 2013). Criteria are needed for making judgements about the rigour of the evidence and the quality with which a specific study has been conducted. In addition, there is an absence of agreement about the standards of evidence that can be applied to research informing social policy. Scientific evidence can also be used in more indirect ways, not having a direct influence on decision-making but being used for shaping attitudes and ways of thinking. This aspect is taken up later in Section 4.2, when the various functions of policy advice are addressed.

To be more specific about evidence, the term 'evidence-based' or, as employed in this report, 'evidence-informed', refers to certain styles of justification and legitimation widely endorsed as a basis for good governance. The historical, epistemological and social backgrounds of such styles have been studied in several interacting and overlapping layers of academic traditions, from basic disciplinary science, through interdisciplinary problem-oriented science, to meta-studies of evidence, to citizens and publics.

Historically, the social aspects of scientific knowledge have been addressed since Fleck's (1935) foundational work on the contingent emergence of scientific 'facts'. Although the role and functions of evidence have differed, the perspective of the (first person) knowing agent has been historically dominant, seeing, hearing and judging for oneself in order to establish some matter of fact beyond doubt. Early modern practices introduced the notion that any rational person would reach the same conclusion about a given state of affairs, only by following a pre-established rational procedure. In law, direct testimony of a credible first-hand witness in front of a jury came to be preferred over hearsay and handed-down knowledge (Shapiro, 2000). In science, direct public demonstration of facts and laws of nature to a community of rational observers was equally essential (Poovey, 1998; Shapin, Schaffer, & Hobbes, 1985; Shapiro, 2000).

Practices of evidence production and appraisal needed to include and address not only experts, but also lay witnesses, fact-finders and audiences (Shapiro, 2000). This propensity of evidence extending beyond special interest groups towards a broader public to establish credibility, trust and legitimacy forms a major social function of evidence. Such functions and their associated values of justice and truth are not necessarily part of the mainstream understanding of evidence, which is traditionally strongly associated with factual and expert knowledge (Poovey, 1998). Yet most practices of evidence presentation and appraisal are deeply embedded in — and oriented towards — social values of legitimacy, trust, impartiality and credibility.

Until well into the 20th century, the main evidence appraisers were the relatively small disciplinary communities of peer reviewers (Bernal, 1939; Ravetz, 1971). However, this started to extend in the early 1970s, as scientific expertise was increasingly brought to bear directly on practical and societal problems. This period saw the birth of evidence-based policy, first in medicine and later spreading throughout most policy areas. Impact assessments were introduced into policymaking (Bimber & Guston, 1997). Integrated computer models (such as those of the Club of Rome (2019) and later climate models) were introduced in direct response to disciplinary sciences that were seen as reductionist and incapable of structuring the salient scientific facts and political problems. In the 1990s and early 2000s, such efforts gained major traction, as interdisciplinarity and 'science in the context of application' became predominant tropes in knowledge production (Gibbons et al., 1994; Nowotny, Scott, & Gibbons, 2001). Augmenting the strong social and economic drivers of these changes, scientific research was increasingly the domain of distributed teams and networks, enabled by large global infrastructures in fields such as epidemiology and climate change (P. N. Edwards, 2010). The salient facts and pieces of evidence involved in present-day evidence appraisal are subjected to a much greater variety of claims, values and interests targeting what should count as evidence (Funtowicz & Ravetz, 1993).

Epistemologically, 'evidence' refers to the available body of propositions or information that we have particularly good reasons to believe to be true and we use in order to justify our beliefs and actions, even in view of a general fallibility. However, untameable scientific uncertainty (van der Sluijs, 2005), the complex relationship between facts and values (Latour, 1987; Longino, 1990; Rudner, 1953), the (partly irreducible) plurality of perspectives on evidence (Ginzburg & Davin, 1980) and scandals of the abuse of evidence to satisfy political or economic interests (Benessia et al., 2016) all potentially undermine public belief in privileged epistemological status. Among the scholars to offer illuminating diagnoses for these pathologies are Porter (1995) (quantification thrives only when the quantifiers are trusted) and Ravetz (1971, p. 179) (fixing an ailing field of science requires 'delicacy'; 'the more subtle components of method are not easily accessible to anyone who has not already invested a part of his[her] life in working in the field').

There are other potential definitions; certain scholars see evidence as a clue or trace (Ginzburg & Davin, 1980; Rheinberger, 1997) of a natural and/or social event. Present policymaking, infused by science and technology, stretches existing understandings of evidence by an increased focus on factual descriptions of possible futures (the science of 'what-if') (Ravetz, 1997). New modalities of evidence emerge from the use of predictive simulation models and from widespread uses of forecasting and foresight.

Given this background, the state-of-the-art comprises overlapping approaches to the concept and role of evidence and its appraisal for policy support. Firstly, through the distinct sciences involved in evidence production with their respective best practices. This varies from single disciplines to evidence-based medicine with systematic reviews, to technology assessment and integrated models, to the literature in organisational and management science in the 1990s (Solesbury, 2001). Secondly, reflecting on how evidence-for-governance remained problematic as practice and concept, various meta-analyses have evolved (in research institutes and governance institutions), often targeted towards improvements of evidence-for-governance (Cartwright & Hardie, 2012; Rutter & Gold, 2015).

The interwoven epistemological, institutional and socio-cultural dimensions of evidence have become more evident since the 2000s, as also basic disciplinary science was seen by many as becoming mired in problems of reproducibility (Ioannidis, 2014), fraud (Benessia et al., 2016) and lack of trust (Benessia et al., 2016). However, as already emphasised, the widespread worries about a growing 'reproducibility crisis' may have been exaggerated and have more recently been questioned (O. H. Petersen, 2019). Fanelli (2018), on the basis of meta-research studies, concludes that the problems that undeniably do exist, and have always existed and will always exist (Gristwood & Breithaupt, 2019), are not distorting the majority of the literature. Furthermore, there is no evidence that the problem is growing (Fanelli, 2018; Gristwood & Breithaupt, 2019).

As the outgoing Director-General of the European Molecular Biology Laboratory, Iain Mattaj, explains in an interview (Gristwood & Breithaupt, 2019), the reproducibility problems have largely occurred in the field of cancer signal-transduction studies in a phase that is now finished, because much better quantitative methods have become available. Although the anxiety about the consequences of outright fraud have not gone away, even those particularly worried about this problem have to admit that the majority of fraud cases occurred in China and predominantly affected publications in very low impact (mostly predatory) journals (Byrne, 2019). Given that articles in such journals, by definition, are hardly ever cited, it is obvious that they are not taken seriously by mainstream laboratories and therefore will not have any influence on scientific developments. Clearly, continued vigilance is important and there are many measures that can and are being used to combat reproducibility problems (Gristwood & Breithaupt, 2019; O. H. Petersen, 2019). In the context of the different opinions about these problems, it is important to keep in mind that empirical science is essentially a self-correcting process in which knowledge is constantly being questioned, revised and expanded (O. H. Petersen, 2019).

Simultaneously, the sciences have become ever more deeply involved in addressing societal challenges, industrial policies and markets. Thus, Science and Technology Studies scholars and others have analysed the phenomenon of 'regulatory science', i.e. forms of knowledge specifically developed in order to deal with the regulatory process regarding food, pharmaceuticals, consumer products and related areas (Jasanoff, 1990; Weinberg, 1972).

When making sense of science, it is important to be aware that there is not a single scientific method or approach but that, within the various traditions and disciplines, a range of different styles of scientific reasoning can be distinguished. The concept of styles of reasoning stems from historical epistemology (Crombie, 1994; Hacking, 1982, 1985). Building on early versions of Crombie's typology, Hacking identified the different styles of reasoning that characterise how different academic disciplines and practices over the past 400 years arrived at scientific propositions that determine what counts as rational or irrational, scientific or quasi-scientific, valid or invalid evidence, true or false. These include styles such as postulation (mathematics), experimental exploration, hypothetical construction of analogical models ('knowing is making'), ordering of variety by comparison and typology, and statistical analysis of regularities and probabilities.

At the science-policy interface, we find messier hybrid and pragmatic styles of reasoning on evidence. Examples of styles of reasoning at the science-policy interface are:

- The weight of evidence approach (e.g. Gough, 2007);
- Systematic reviews and meta-analysis (e.g. Pullin & Stewart, 2006);
- Decision trees (Cramer, Ford, & Hall, 1976);
- Threshold of toxicological concern (TTC) (Kroes, Kleiner, & Renwick, 2005);
- Tiered approach in risk assessment (e.g. Garcia-Alonso et al., 2006);
- Precautionary reasoning (e.g. Beyleveld & Brownsword, 2012);
- Integrated assessment and integrated assessment models (van der Sluijs, 2002); and
- Consensus approach (e.g. van der Sluijs, van Est, & Riphagen, 2010).

Such styles of reasoning prescribe what counts as valid and sufficient evidence to settle scientific disputes, meet desirable public and political agendas and legitimate policy interventions to govern complex, uncertain and controversial issues (see also Kriebel, 2008, 2009).

3.4 PLURALITY OF KNOWLEDGE BEYOND SCIENTIFIC INFORMATION AND EVIDENCE

In today's technologically-dominated world, different branches of science inevitably deal with increasingly complex questions. Moreover, some areas of scientific study, e.g. the environment, the human brain or our economic behaviour, may inherently be more complex (at least in technical terms) than others. The social and political conditions under which scientific advice is provided add to this inherent complexity of science and pose a challenge, both for those providing science-based advice and those in receipt of such advice. In this section of the report, we will examine the ways in which different, at times, competing knowledge claims may further complicate the task of providing good scientific advice.

That there are many forms and sources of knowledge, beyond what is available through the various methods of scientific investigation, is a near-platitude. Yet there are circumstances where this commonly-recognised plurality of knowledge sources and claims gives rise to difficult questions about how to generate and convey policy advice. Two specific difficulties are particularly noteworthy.

All knowledge claims, scientific or otherwise, begin within a framework of prior assumptions and intuitions. Such prior assumptions can vary across differing cultural traditions and histories, as well as with personal and group experiences and inclinations. The conflicting belief sets and knowledge claims arising from such differences are often difficult to reconcile, as their ultimate source is a set of background beliefs that are not necessarily open to further scrutiny. They thus give rise to what are known as 'deep disagreements' — disagreements where there is a clash between the very frameworks that embed differing knowledge claims (Fogelin, 1985, p. 8).

Scientific evidence that comes into conflict with deeply-held beliefs, and is at variance with its claims, will face obstacles in providing effective and convincing policy guidelines. The difficulty is augmented by the fact that non-specialists, those who learn about science indirectly, have to rely on testimonial knowledge in approaching problems and issues defined according to the terms and assumptions of scientific expertise (Lipton, 1998), i.e. knowledge acquired by what we learn second-hand from those who have first-hand knowledge of the field. The acceptance and commitment to testimonial knowledge, in turn, involves a large measure of 'blind' trust, i.e. trust without recourse to a strong evidence base. As we will see in a later chapter, the question of trust in science introduces complexities of its own.

A second type of conflict between science and other forms of knowing may be even more serious. Scientific knowledge claims standardly take the form of propositions that are deemed at least provisionally, true or reliable, but crucially also justified (Mizrahi & Buckwalter, 2014). A distinctive feature of many scientific knowledge claims is their universality. The criterion of justification for a scientific claim is assumed to be invariant across different cultures and contexts (Kuukkanen, 2011). This, however, is not necessarily true of our intuitions of what counts as knowledge and justification in our daily lives. Different standards and criteria of justification can apply in different contexts and types of knowledge claim, and in different spatio-historical environments. A crucial question, then, is how to compare and rank knowledge claims generated through the methodologies of science against other forms of knowing. Should policymakers privilege, or even give equal status, to science over the long-established dictates of local knowledge? Science has given humanity the most rigorous of methodologies for gaining information about the world. However, the question whether the scientific method invariably provides the best approach in dealing with all areas of our social and individual lives is still debated (Stueber, 2012).

The pejorative term 'scientism' (Haack, 2003) is often used to characterise the privileging of scientific knowledge, at the expense of local traditions and insights from other branches of learning and culture. Such privileging, many have lamented, has created what Max Weber called a 'disenchanted world' (M. Weber, 1946, p. 139). At what stage a well-justified belief in the effectiveness of science in providing solutions to some of the problems facing humanity becomes scientism is an important question that bears serious consideration.

3.5 DEALING WITH NORMATIVE ISSUES AND ASSUMPTIONS: KNOWLEDGE, INTERESTS AND VALUES

It seems natural to think that there are unavoidable connections between the activities of science and the ethical and social values that govern our public life. However, the relationship between science and the realm of values is far from straightforward. On the one hand, it has been argued, 'science is a product of human activity, and as such it inevitably involves a wide variety of value-laden choices and judgements, many of which have ethical dimensions' (Doyle, 2018, p. 18). On the other hand, the quest for objectivity, where being objective is defined as freedom from value judgements, personal and local interests has been seen as one of the defining and most valuable features of the modern sciences at least since Francis Bacon (Padovani, Richardson, & Tsou, 2015). It has been the main argument of Hilary Putnam (1981) that rationality is neither a subjective reference point (relativism) nor an objective universal yardstick (positivism), but relies on a social process of rational reasoning that includes the factual power of values and the value dimensions of facts. Both are interwoven.

According to this approach, science deals with facts, while value judgements come into the picture at the level of actions and affects the decisions we take about how to utilise science: the decisionistic model of science advice (Maasen & Weingart, 2005). However, even if scientific knowledge can be impartial and non-partisan, it is never unconditional. It is always based on norms of methodology, (subjective) choices of topics and methods, schemes of data processing and interpretation, and selection of application contexts (Latour, 1987; Latour & Woolgar, 1979). Hence, the dichotomous picture of facts versus values has come under pressure from various sources, but the pressure is most evident when science becomes involved in policy decisions and when complicating factors such as uncertainty, complexity and ambiguity are brought into the picture.

Two distinct approaches have dominated discussions of the role of values in science. The first strongly argues that the acceptance or rejection of a scientific theory should be based only on the empirical evidence available and hence completely value-free (Lacey, 1999, pp. 214-215). For example, Hugh Lacey, a strong voice in this tradition, argues:

> *‘we would be thrown back on merely ‘wishing’ the world to be a particular way or the back and forth play of biases, with only power to settle the matter’*
>
> (Lacey, 1999, pp. 214-215).

The key point that the advocates of a value-free science make is that our values and interests should not affect our knowledge about the world. Values dictate our actions and decisions but not the findings of science. However, what the advocates of a value-free science tend to underestimate or ignore is the role of values and interests in the decisions scientists take regarding the pursuit of a particular scientific project and, even more crucially, the weight they assign to available evidence in accepting a particular scientific theory (Douglas, 2009).

The second approach emphasises the ever-present role of values in the conduct of science, as well as in its application. Scientists make value judgements in choosing research topics and goals; in staffing their research projects, for instance, in using students or excluding certain categories of researchers (e.g. women or non-whites); when dealing with the use of human subjects and animals; in their choices of the methods for dissemination; and in applying research findings (see, for instance, Rescher, 1980, 2013; Rudner, 1953).

In the context of the intersection between science and policy advice, the most crucial value judgements come to the fore when deciding where to set the bar on the standards of proof for a scientific theory. Indeed, the ethical questions relevant to the standard of evidence required and thereby the strength of scientific recommendations in policy decisions are perhaps the strongest examples of how the established procedures of science intersect with value judgement. The question of what level of evidence is sufficient for deciding to rely on a scientific theory for a policy decision cannot be free of value judgements. As Rescher writes:

> *‘This problem of standards of proof is ethical, and not merely theoretical or methodological in nature, because it bridges the gap between scientific understanding and action, between thinking and doing…’*
>
> (Rescher, 2013, p. 208)

The problem of standard of proof is particularly acute for science-based decisions taken under conditions of uncertainty, complexity and ambiguity. The issue was first highlighted by Karl Hempel (1965) and has been discussed more recently by philosophers of science (Douglas, 2009), as well as many feminist epistemologists (e.g. Anderson, 2004).

The question of introducing values in scientific procedures is most relevant in connection with the 'inductive risk' inherent in science. Karl Hempel is the source for the classic expression of the point. He writes:

> *'acceptance of any scientific law carries with it the 'inductive risk' that the presumptive law may not hold in full generality and that future evidence may lead scientists to modify or abandon it'*
> (Hempel, 1965, p. 92).

Any scientific theory may turn out to be false, in part or as a whole, when new evidence is found or existing evidence is re-interpreted. This is a well-known feature of the conduct of science. In the face of such possibility, scientists have to make decisions regarding the standards of evidence required for accepting a particular claim or theory (Kitcher, 2011). An adequate decision process should consider the risks of accepting a theory as true when, in fact, it is false and the loss of benefit that will ensue if a true theory was not accepted (Douglas, 2009).

Any decision as to the loss of benefits when rejecting a theory or the severity of risk in accepting a theory will involve value judgements (Kincaid, 2007). In particular, the question of how many false positives or false negatives make a postulated theoretical relationship obsolete provides a major value judgement that cannot be derived from the evidence itself (Biddle & Kukla, 2017). It relies on conventions among the respective scientific community (for example, the rule of 95% significance level as sufficient for accepting a functional relationship (Rosnow & Rosenthal, 1989)). The challenge is even more serious when a scientific theory is used as evidence to guide public policy. In such cases, values and weighting of interests will be central because of the potential consequences of error (Biddle & Kukla, 2017).

3.6 PROCESS: SCIENCE AS ADVICE TO POLICY

It is useful to make a distinction between the different roles scientific evidence might play in science policy contexts. The evidence and advice may, for instance, serve as a steering mechanism, as a key to learning, or as a connective element of decision-making (van Der Molen, 2018). Different types of evidence and advice come with different forms of interaction between research and research policy. Information circulates in knowledge systems that encompasses multiple knowledge claims, groups of actors, and ways of creating and exchanging knowledge (Evans, 2010; O'Toole & Coffey, 2013). Considering the evidence base in this field, three elements within the provision of scientific advice appear especially significant:

- Mechanisms of quality control;
- Questions of the efficacy of scientific advice/information;
- The norms and expectations at intersections of science, policy, and practice.

Quality control

In general, evidence for science advice for policy is regarded as of high quality when it is viewed as professional, unbiased, and inclusive. At the same time, a wide range of studies has identified the importance of acknowledging that different groups of actors involved in evidence for policy have different 'ways of knowing', and may think quite differently about what constitutes the proper perception of problems, which factual knowledge is relevant, what constitutes reliable evidence and procedural fairness (Cash et al., 2003; S. K. H. Janssen, van Tatenhove, Otter, & Mol, 2015; Van Buuren, 2009).

Different ways of knowing may require distinct criteria for quality control and accountability mechanisms. Especially with contentious issues, when stakes are high, when there is substantial scientific uncertainty, or when there is great urgency for decision-making (Funtowicz & Ravetz, 1993), the question of the *relevance* of the evidence for the problem or the question at hand is very important for assessing the quality of the information. These processes will have a higher chance of success when researchers accurately distinguish between what is known with great certainty, and what is less certain or where knowledge is contested. It is equally relevant to assess how the evidence has impacted the problem definitions and framing of the issue space (Cash et al., 2003). Also, recognised authoritativeness may help in establishing the quality of a scientific opinion, but such a way hides always the risk of falling into frozen pre-concepts supported by an *ipse dixit*, i.e. an unproven statement.

Efficacy

The concept of quality as applied to scientific evidence is not the same as quality in the deployment of the evidence for policy. For example, an excellent scientific quality may simply be ignored, or miscommunicated accidentally or instrumentally, with a resulting poor policy decision, while — at the opposite extreme — a modest scientific quality may end up being sufficient for the purpose of reaching a desirable policy compromise. Evidence for science policy is considered to be most effective when it is seen by relevant actors as credible, salient, and legitimate (Cash et al., 2003). Credibility refers to the scientific adequacy of the epistemic, technical and empirical basis of the research; salience refers to the relevance of the evidence and information for policymaking; and legitimacy refers to the level of awareness of the different value systems that may come with different ways of knowing. These three features of successful provision of evidence and advice are intimately connected, which means that doing well on all three criteria is quite a challenge (Cash et al., 2003).

Intersections

In order to facilitate the development and diffusion of high-quality (authoritative, unbiased, inclusive, credible, salient, legitimate) advice for policy, it is crucial that the interfaces between different knowledge systems are properly managed (Bremer & Glavovic, 2013; Clarke et al., 2013; Wesselink, Paavola, Fritsch, & Renn, 2011). This is not simply a matter of creating the best institutional interface, but also of the weighting in specific practice of the various scientific inputs and opinions. This can, for instance, be done by way of ongoing coordination work and knowledge exchange between knowledge providers and policymakers (Jordan & Russel, 2014; Robinson & Wallington, 2012; Wyborn, 2015). Such forms of coordination and exchange are especially relevant when different actors 'enter the debate under different concepts of what makes information salient, credible, and legitimate' (Cash et al., 2003). Effective quality control mechanisms encourage communication, negotiation, and translation across all actors operating at the intersection of research, policy, and practice.

3.7 CHALLENGES: DISSENT, IGNORANCE AND UNCERTAINTY

Scientific advice can play different roles in different policy and decision contexts. Evidence and advice can crucially influence the decision-making process and compel action in a context where there is a broad agreement on underlying values and problem definitions, and the level of uncertainty is low (Pielke, 2007). In many cases, however, decisions on important issues must be made under conditions when 'facts are uncertain, values in dispute, stakes high and decisions urgent' (Funtowicz & Ravetz, 1993).

In general, knowledge claims by scientists undergo peer review. For instance, through *ad-hoc* review panels or by letting the opinions percolate within the scientific community, waiting for reactions if any (if there is time enough). However, the recognised competence of a panel of advisers is not in itself a guarantee. For those questions which are not dramatically urgent, the broad opinion of the various scientific communities implied in the tailoring of the answer can be a useful filter; for instance, through the publication of a discussion document or the organisation of ad-hoc meetings.

In the simple 'linear' or 'deficit' model, it is assumed that when all available facts and information are communicated to the public and policymakers, an agreement on scientific evidence leads to policy consensus and determines the decision to be taken (Hilgartner, 2000; Alan Irwin & Wynne, 1996; Jasanoff, 1991). In reality, different explanations can account for the available evidence, and there is no unique path to a specific decision. This is especially true when participants in a decision-making process do not share common objectives, or there are conflicting commitments based on different values (Pielke, 2007). In such cases, decision alternatives cannot be contrasted solely on the basis of scientific evidence. Rather, value conflicts and competing problem framings have to be resolved or taken into account in reaching a decision (Grove-White, Macnaghten, Mayer, & Wynne, 1997).

The articulation of values and alternative perspectives guides the selection of evidence and helps identify decision alternatives. Resolving — or least clarifying — value conflicts improves communication and interaction between stakeholders. Practical initiatives in this direction, which aim both to open up ethical matters and take account of different forms of evidence and understanding, have already been taken and deserve greater discussion (e.g. Lindner et al., 2016; Rip, Misa, & Schot, 1995; Stilgoe, Owen, & Macnaghten, 2013).

The process looks unproblematic in the case in which there is a general consensus in the scientific community, the question for consultation is restricted and the range of the estimated uncertainties is small. It may become harder whenever the disagreement among scientists grows strong. The question then is whether scientists must limit their role to faithfully communicating the uncertain state-of-the-art and letting politicians handle the technical matter (on which they have conceivably little or no competence), or whether scientists must take the responsibility to distil a chart of pros and cons for each of the competing positions.

The matter is even harder when the question posed to science is either too vague or requires answers that go beyond the scientific domain in which the question is asked (trans-scientific), as the tailoring of an answer may imply competences which do not fully overlap. The solution to this very delicate case requires one of the following options:

1. When the question posed is vague, to consult with those requesting the advice and explore whether the question can be reframed in a more defined and scientifically-specific form.
2. For either vague or trans-scientific questions, to define one or more well-defined interpretations of the question for which evidence is available and provide advice on each of them; an open assembly of a cluster of opinions which stresses the composite nature of the final advice.
3. However, choosing an option would imply that the advice given to policymakers clearly distinguishes which answers can be derived from the evidence and which represent the prudent judgements of the advisers.

In summary, science has the responsibility to provide frank and evidence-informed answers to policy questions, stressing:

1. Whether these questions are well-posed or not;
2. Whether there is only one correct answer to the question or many potentially correct answers (as science is not exact);
3. How the level of scientific reliability is characterised;
4. What the pros and cons are of each of multiple solutions;
5. The robustness of the evidence presented;
6. What assumptions and values have been included in the analysis and how sensitive the results are when assumptions and default values are changed.

Science-related public controversies can have different origins but they arise especially when evidence is conflicting or ambiguous, decision stakes are high, and uncertainty is large (Epstein, 1996; Nelkin, 1992). However, in many cases, public disagreement on specific issues involves conflicting values, understandings, beliefs and interests, rather than scientific information alone. Conflicts may also be driven by deliberate or non-deliberate manipulation of the scientific data. The values, beliefs and interests that affect how evidence is perceived and interpreted can be political, economic, religious, and cultural or a combination thereof. In addition to advice-givers and decision-makers, many stakeholders and laypeople participate in discussions on contentious issues, thus at least potentially contributing to the complexity of perception of scientific evidence. In particular, 'the voices of organised interests and influential individuals are amplified in public discourse' (National Academies of Sciences Engineering and Medicine, 2017).

Emerging issues in the science advisory process include the growing interest of civil society in scientific advice (Organisation for Economic Co-operation and Development, 2015). Specifically, citizen science has emerged as a significant phenomenon, often crossing the established boundaries between science and democratic engagement (Hecker, Haklay, Bowser, Makuch, & Vogel, 2018). Whilst citizen science can be defined in different ways (Bonney, Cooper, & Ballard, 2016), in one form it involves the 'engagement of non-scientists in true decision-making about policy issues that have technical or scientific components' (Lewenstein, 2004).

Modern science has become more socially embedded and both the public and policymaker focus on the accountability of scientific research and its applications (Jasanoff, 2012). This is especially true in the case of 'issue-driven' science, characterised by highly uncertain and/or contested evidence and high decision stakes (Funtowicz & Ravetz, 1993). The involvement and participation of people outside established scientific institutions is valuable in gathering and evaluating evidence, assessing the costs and benefits, and estimating risks. As a part of policy implementation, public engagement could be particularly important for trans-disciplinary applications, for which evidence and uncertainties are integrated from different scientific fields (Alan Irwin, 1995). Geographical distribution, different policy application areas, the level of engagement and type of activity influence the involvement of citizen science in policymaking (Haklay, 2015).

Citizen science can provide high-quality evidence relevant for decision-making, but these facts and information are, in most cases, obtained and produced by methods that differ from those employed by scientists and established research organisations (Hecker et al., 2018). To ensure sustained influence on the decision-making process it is, therefore, important to develop durable and methodologically reliable procedures for verifying the quality of evidence obtained by citizen science and provide incentives for collaboration between scientists and people from outside scientific institutions (Aisling Irwin, 2018). However, this must not prevent citizen science from introducing 'novel viewpoints, radical critiques, or considerations lying outside the taken-for-granted framing of the problem' (Jasanoff, 2012).

The implication from much of the growing literature on citizen science is that it can play a role within the scientific advisory process, not least by expanding the range of evidential sources and providing a partial re-framing of policy-related questions (Aisling Irwin, 2018). However, there are also many critical voices about the reliability and function of citizen science (Guerrini, Majumder, Lewellyn, & McGuire, 2018). Concerns are raised about the integrity of science (retaining the methodological rigour that is neded for conducting science), the issue of intellectual property (who is the owner of the knowledge generated by citizens) and on the image of science that is being conveyed to citizens (citizens collect data, professional scientists make the interpretations).

Chapter 4: Using scientific evidence in policymaking contexts

4.1 THE FUNCTION OF SCIENTIFIC EVIDENCE IN POLICYMAKING

What is the function of scientific evidence (and related advice) in policymaking? To address this question, we need to consider, first, how the role of scientific advice in modern democracies is typically represented; and second, what we have learned about this role from in-depth studies of scientific advisory processes in practice.

In public and political discourse, the most familiar representation of the relationship between scientific advice and policy is one in which authoritative advisers present the analysis and 'the facts' for policy- and decision-makers to use (Hutchings & Stenseth, 2016). Advisers may be called upon at various points in policy formation (which is itself often assumed to be a linear and rational process). They might be asked, for example, to delineate a problem or/and to advise on the likely efficacy of potential policy solutions; or they might be called upon to inform decision-making in a crisis.

Some advisers and advisory bodies offer counsel in an ongoing way, while others may be consulted on a 'one-off' basis. In any case, the model of rational analysts within an essentially linear policy process embodies a separation of 'science' and 'politics'; scientific advisers (and other experts) are seen as offering disinterested, objective advice, while it falls to political actors to make judgements of value (Manwaring, 2018). This representation of relations between science and policy, as mediated by expertise, is so frequently reiterated, especially in the context of science–policy controversies, that it tends to be taken for granted (Halligan, 1995). It is implicit, for example, in the often-repeated calls for 'evidence-based policy'.

A second model is almost equally familiar, though paradoxically it is quite different from the first in its representation of the function of scientific advice. It is a model in which scientists and other experts are frequently called upon to give advice but their input (or even their existence) is used selectively and/or strategically to legitimise political choices or depoliticise contentious issues (Craft & Howlett, 2012). 'Waiting for the facts' is a time-honoured way of deferring the moment when a difficult decision must be made; as Harold Macmillan recognised in the 1950s (when under pressure about urban air pollution), forming a committee is a good way to 'seem to be very busy' whilst not actually having to do very much (UK Cabinet Office, 1953). Further, in complex and contested areas of policy, it is demonstrably possible to use evidence and advice selectively (by turning to particular advisers or 'cherry-picking' findings and recommendations) to support policies or decisions that are politically expedient. Policymaking, in this model, is driven less by evidence than by what Kingdon (2003, p. 163) calls 'the balance of organised forces'. Science and other forms of knowledge might even be seen as epiphenomenal — not featuring among the key, independent variables affecting policy outcomes — and in this sense the function of expert advice is essentially symbolic (Newman, 2017).

An interesting feature of these familiar representations — the 'linear-rational' and the 'strategic' — is that the former is often invoked while the latter is widely suspected (Owens, 2015). Both are instantly recognisable, in part, because they are so frequently rehearsed but also because we can find elements of each, in particular circumstances, in real-world advisory practices. However, neither provides a fully adequate account of the subtle interactions that in reality characterise the so-called 'science-policy interface' (Owens, 2015).

The 'linear-rational' model has been the subject of a wide-ranging scholarly critique, most notably on grounds of its unrealistic assumptions about the rationality of the policy process, the neutrality of experts and the function (and construction) of evidence and advice (Parsons, 2002). Nor, it seems, does the model work very well in practice: as is evident in much contemporary conflict, claims that policies and decisions are 'science-based' do little to reassure protagonists when complex and contested issues are involved (Marston & Watts, 2003). Overall, as Stephen Turner (2013, p. 4) has argued, 'little about this [linear-rational] model is *not* misleading'.

The 'strategic' model is problematic, too, even if it sometimes feels closer to reality (Owens, 2005). If knowledge was of little independent significance in policymaking, how should we explain the evolution of policies that do seem, broadly, to 'follow the evidence', especially when we take the long view? European environmental policy, for example, would hardly have taken its present form had it not been for the vital contributions of environmental science over the past half-century or so.

Over a broadly similar period, social scientists have sought better understandings of policy processes, knowledge-making and the interactions between the two (e.g. Barker & Peters, 1993; Bulmer, 1980; Clark & Majone, 1985; Collins & Evans, 2007; Hajer, 1995; Hall, 1993; Lentsch & Weingart, 2011b; Owens, 2015, 2016; Pielke, 2007; Renn, 1995; Sabatier, 1987, 1988). In recent decades, scientific advice and other forms of expertise have themselves become an increasingly important subject of investigation, and we can draw insights from a growing number of in-depth studies of particular advisory institutions (e.g. Bijker, Bal, & Hendriks, 2009; Hilgartner, 2000; Jasanoff, 1990; Owens, 2015). This body of work shows clearly that the functions of evidence and advice in the policy process are both complex and contingent. It suggests that the 'linear-rational' and 'strategic' models outlined above, while retaining a degree of validity, account only in part and in special circumstances for observed interactions and outcomes. When problems are well-structured, for example, scientific advisers might indeed act primarily as rational analysts, providing broadly consensual evidence that political actors can readily deploy. Yet the reality is almost always more subtle. In detailed studies of real-world advisory practices, expert advisers emerge as cognitive and discursive agents, not only in possession of vital epistemic skills but also implicated in interactive and essentially social processes like those of 'policy learning' and 'boundary work'.

In the former capacity — as agents of policy learning — expert advisers analyse and synthesise, develop ideas, (re)frame problems, and find effective ways of presenting evidence and articulating their arguments (Lentsch & Weingart, 2011b). Sometimes the effects of their advice may be simple and direct (with echoes of instrumental rationality) but in many cases there is a slower, more discursive process of learning, the effect of which is 'gradually to change the … vocabulary and interpretative frames of policy-makers' over time (Radaelli, 1995, p. 164). In these ways, advisers have been shown to exert indirect, 'atmospheric influence' (James, 2000, p. 163) and to contribute to the long-term process that Carol Weiss has called 'enlightenment' (Weiss, 1975; 1977, p. 531; 1991). The implication is that scientists may have to be patient if they want to see the impacts of their evidence and advice.

The concept of boundary work has also contributed substantially to an understanding of practices and outcomes in science–policy interactions. In particular, we have learned that as well as cultivating authority by constructing and defending boundaries between 'science' and 'non-science', as Thomas Gieryn (1983) first envisaged, many advisers simultaneously find ways to bridge these boundaries, framing their arguments and recommendations so that they make sense in the worlds of science and policy alike. So, for example, Sheila Jasanoff (1990, p. 237) found that expert scientific committees advising US Federal agencies were adept at producing 'serviceable truths', capable of meeting these hybrid criteria; Wiebe Bijker and colleagues, exploring the work of the Health Council of the Netherlands, found that this long-standing body succeeded '… in preserving the role of an independent and credible scientific institution' (Bijker et al., 2009, p. 163), primarily by 'distinguishing and co-ordinating' the worlds of science and politics in ways that were beneficial to both (Bijker et al., 2009, p. 149). Similarly, in an in-depth study of the practices and influence of the UK Royal Commission on Environmental Pollution, which advised governments over a period of more than forty years, Owens (2015, p. 168) concluded that:

> ***'The Commission was never simply a detached conveyor of analysis and information, nor a cipher whose advice was epiphenomenal…The evidence points, instead, to a combination of brokering and 'educative' functions, as envisaged in cognitive models of the policy process, with practices such as boundary work, associated with the idiom of co-production'.***

The idiom of co-production offers a conceptual framework for discussion of 'relationships between the ordering of *nature* through science and technology and the ordering of *society* through power and culture …' (Jasanoff, 2004a, p. 14). In this sense, the co-production of science and politics in expert advisory practices is an example of 'the ways in which we know and represent the world' being 'inseparable from the ways in which we choose to live in it' (Jasanoff, 2004a, p. 2).

The evidence from many studies to date shows that scientific knowledge does indeed matter in the policy process, but never in isolation (Dryzek, 2006). Rather, it has effect in conjunction with a multiplicity of other variables, including, for example, the tractability of the issue at hand, the nature of the evidence and associated uncertainties, the skills of expert advisers (epistemic and discursive), and the receptiveness of the political environment — and always within the broader context of interests, institutions and power (Parkhurst, 2017). Moreover, given the plural nature of values and societal norms, science advice needs to be integrative in mapping the common, complementary and adversarial propositions about an issue in question (Stout & Love, 2018).

The combination of issues and circumstances will influence which functions of evidence and advice come to the fore, and the complexity and contingency of interactions among knowledge, policy and expertise help to explain why advice is at various points accepted gratefully, used strategically, absorbed in diffuse ways, or ignored (Jasanoff, 1990). For these reasons, we might best think of the influence of scientific knowledge and advice in terms of a spectrum or continuum of effects (Owens, 2015), with rapid and direct impacts (such as tangible shifts in policy) at one end and diffuse, long-term conditioning of the policy environment (which may not be readily visible or attributable) at the other. Changing the frame would be an example of a slower, more diffuse form of influence, which may nevertheless be of considerable importance (see also Section 4.3.3).

4.2 THE NEEDS OF POLICYMAKERS: A CLASSIFICATION OF FUNCTIONS OF SCIENCE FOR POLICYMAKING

Within the spectrum of various functions that scientific advice can offer to policymaking, the simple model of 'truth speaks to power', as well as the 'strategic' model of policymakers seeking justifications for their policy choices, are two extremes that do not match the needs of policymakers for robust and reliable knowledge in a complex and contested problem space (National Research Council, 2012; Pielke, 2007). In order to make this range between the two extreme positions more tangible for designing the interplay between science and policymaking, it is useful to distinguish five functions that reflect the needs of policymakers with respect to scientific input:

1. *Enlightenment:* being informed about the state-of-the-art of factual issues (descriptions) and causal/functional relationships that form reliable knowledge (for example, the relationship between CO_2 emissions and climate change).[2]

2. *Orientation:* making oneself familiar with and gaining a more in-depth understanding of a challenge or a problematic situation, including visions and plans for future actions (for example, addressing the problem of water scarcity due to climate change and providing scenarios or foresight assessments for dealing with the problem).

3. *Strategic planning:* providing strategies for reaching a predefined goal or objective that meet the purpose and make the side-effects of each strategy

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[2] 'Enlightenment' here is used in the sense of being well informed about the current state of knowledge. Weiss (1975, 1977, 1991) uses the term rather differently in describing the gradual, longer-term impacts of scientific knowledge on policy. There is of course some overlap in these meanings.

transparent to the decision-maker, including uncertainties and ambiguities (trade-offs) (for example, developing and assessing various strategies to reach 80% renewable energy in the year 2050).

4. *Integration:* bringing various forms of knowledge — for example, scientific, experiential, anecdotal, place-based and indigenous knowledge — into a coherent framework (Renn, 2010) and a common understanding (as far as this is possible).

5. *Co-creation of knowledge:* engaging representatives of science, civil society, politics, private sector and/or the affected public(s) in designing new insights or options that facilitate the creation of innovative solutions to a given problem or challenge (for example, developing a new understanding of how to design a smart urban environment that is sustainable, protects human rights and adds service functions for its users).[3]

This list is not exclusive but points to the main needs with respect to scientific input to policymaking (see Lentsch & Weingart, 2011b; Organisation for Economic Co-operation and Development, 2015; Parkhurst, 2017; Renn, 1995, 2001; Sanderson, 2009; Wittrock, 1991). All these functions are embedded in the meta-function of *legitimisation* (Weingart, 1999), i.e. using scientific knowledge and advice as an instrument to justify one's own policies or decisions (for example, finding good arguments to justify new migration policies). The following paragraphs will elucidate each of these five functions and describe how they need to be addressed in order to become effective.

4.2.1 Enlightenment

The goal here is to structure and summarise the state-of-the-art in a specific area, topic or domain. If truth claims are contested within the academic communities, an epistemic discourse is necessary to identify and characterise dissent, explore the reasons and causes for the dissent and provide a map of what is reliable knowledge under rigid scientific scrutiny (Edenhofer & Kowarsch, 2015; Weiss, 1977). Uncertainties and ambiguities need to be identified and characterised. Questions such as 'What is the pollution level in location *x* and how does it affect human health?' or 'How much temperature increase do we expect if CO_2 levels double in *x* years?' are typical for such discourses. The main point here is what is — to our best collective knowledge — true? This type of knowledge should be impartial and valid prior to knowing any interests that could benefit from its use (Nutley et al., 2013). However, in practice validation of knowledge in isolation from interests or values may prove difficult to achieve.

For the purpose of enlightenment, we need classic science with the mandate to provide factual insights that can help to avoid painful errors due to false assumptions or 'wishful thinking'. Lentsch and Weingart (2009) address this function as a combination of epistemic and political robustness. Specific methods for such a discourse include

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[3] 'Co-creation', as defined here in terms of a collaborative, problem-solving process, should not be confused with the STS concept of 'co-production', as defined in Section 4.1.

expert workshops, Delphi, Group Delphi, cross-impact-balance analysis and many others (Renn, 1995).

4.2.2 Orientation

The goal here is to develop, in close dialogue with the decision-makers or specific audiences (such as participatory bodies), a vision of how to address a problem or a challenge (Wittrock, 1991). Orientation is always based on a combination of normative assumptions and factual knowledge about the likely implications of different visions (Hoppe, 2005). Such orientation discourses require scientific input in two forms: *factual input* (based, for example, on an epistemic discourse), and *communicative expertise and competence* (which could be called 'catalytic knowledge') for guiding the participants into a discursive process that combines factual knowledge with reflections about values and their implications for future policies (Maasen & Weingart, 2005; Renn, 2018).

The two types of knowledge may not reside at the same institute but it is crucial that the experts for the communicative knowledge are so familiar with the factual topic that they can discriminate between factual, strategic and absurd truth claims. Methods for orientation discourses include, on the one-to-one basis, expert advisory committees (such as the German federal advisory committees SRU or the WBGU) and, on the multiple-actor basis, roundtables, future workshops, foresight activities, and others (Renn, 1995). It is important that these discourses are either clearly related to a specific decision-maker (for example, federal government) assuring open publication of the results, or constitute an open forum of all stakeholders that are affected by the topic under review (Oberthür et al., 2002).

4.2.3 Designing and evaluating strategies

The goal here is to design and analyse strategies that promise to lead to predefined goals (Weingart, 1999). Scientific input for strategic discourses is not neutral but directed towards normative goals or values. It is, in the best sense, *advocacy science* (Horton, Peterson, Banerjee, & Peterson, 2016; Nelson & Vucetich, 2009). Strategic discourses include four major elements:

1. Designing suitable options to reach predefined goals;
2. Assessing and evaluating the effects and side-effects of each option (impact profile);
3. Initiating a discourse with decision-makers on how to resolve conflicting values by assigning appropriate trade-offs;
4. Monitoring the impacts and effects of policy options that have been implemented (Ingold & Gschwend, 2014; Renn & Sellke, 2011).

The goal is to *co-design, evaluate and monitor strategies for reaching a common goal that all actors want to pursue*. This could be energy transition, the safe disposal of nuclear waste, or a reduction in dependence on transportation modes based on fossil fuels. It is essential that such discourses include all the actors that have the power to implement the strategies (Wolf, 2002). A strategy that nobody implements is not worth much. Methods for strategic discourses include roundtables, consensus conferences, citizen juries, and many others that bring together experts and citizens (Renn, 1995). These methods also apply mediation techniques for addressing and often resolving conflicts (Amy, 1987).

4.2.4 Integration

This function rests on the idea of bringing together different disciplinary perspectives but also knowledge from different sources. A division into systematic-scientific, experiential, local and indigenous knowledge is often made in order to classify the various sources of knowledge (Fazey, Fazey, Salisbury, Lindenmayer, & Dovers, 2006; Moller, Berkes, Lyver, & Kislalioglu, 2004; Stevenson, 1996). The scientific input here is to collect the various forms of knowledge, assigning them a specific function or place in an integrated model or synopsis. Sometimes meta-analytic procedures (often narrative synthesis) are used to define common perspectives and insights, but also idiosyncrasies and conflicts. Methods for integration include joint fact-finding exercises, document analysis, meta-analysis and consensus conferencing.

4.2.5 Co-creation

The goal here is to engage participants in a creative and reflective discourse that starts with a diagnosis of a situation or the acknowledgement of a problem, and develops novel and often creative solutions and insights that address the situation or problem at hand (Hoppe, 1999; Jasanoff, 1990, p. 234). The emphasis is on both an attitude of creativity and awareness, as well as a common good orientation. Both components are necessary to gain a better understanding of what is at stake and what needs to be done (Wiek, 2007). The participants are more likely to be *change agents in all fields of society* and less likely to be the incumbents in politics, economics or civil society (Turnhout, Stuiver, Klostermann, Harms, & Leeuwis, 2013). The idea is to develop new, often surprising initiatives and suggestions for changes that could spread from niches to mainstream politics (Mauser et al., 2013). Methods range from future workshops and creativity workshops to vision modelling and living labs (Lang et al., 2012).

In conjunction with these four basic functions, most policymakers have an interest in justifying their decisions as part of their quest for legitimisation, in addition to seeking expert advice 'simply because they want to make the right decisions' (Barker & Peters, 1993). Powerful actors in politics, economics and society are permanently challenged to justify their performance and gain support for their actions. They often seek scientific assistance in order to enhance the legitimacy of their positions and actions (Lentsch & Weingart, 2011b; Weingart, 1999). That is not unethical (it is even necessary in a democratic system), but if scientific input is used selectively to justify interest-driven positions or to find support for otherwise questionable activities, it can become an ethical problem (Eden, 2005). Neither 'greenwashing' nor 'whitewashing' can be in the interest of science dedicated to the common good.

However, all the discourses above, including co-creation, will have the side-effect of providing some legitimacy to the actors involved. This is inevitable and also not problematic, since scientific advice should not only meet the demand of epistemic robustness, but also political robustness (Lentsch & Weingart, 2009). The threshold is reached, however, when the quest for legitimisation exceeds the quest for enlightenment, orientation, strategy or co-creation (Birrer, 2001). Unfortunately, this is a judgement call and there is no principle that can guide such judgements, other than adhering to transparency, openness and fairness, as well as looking at past performance of the respective actors.

In addition to the functions of scientific advice for policymaking, it is important to include the context in which the advice is given. For example, in emergencies and crisis situations, advice to policymakers need to be precise, timely and unambiguous (Salama, Spiegel, Talley, & Waldman, 2004). Scientists may serve as advisers to emergency management teams in cases of an outbreak of contagious diseases, or when natural disasters strike (Aitsi-Selmi et al., 2016). In this context, scientists can provide expertise for improving the preparedness for disaster management, for installing and testing systems for early warning or for designing management options for fast relief.

Other contexts may require other specialised forms of advice, for example, in matters of legal or diplomatic services, international negotiations or mediation between different interest or value groups. There has been a growing literature on science diplomacy, where science advisers are involved in international policymaking across countries or constituencies (Lord & Turekian, 2007; Turekian & Neureiter, 2012). Another important context is the control and monitoring of technology; this involves technical expertise, such as advice to prevent accidents or oversee technological performance (Hoffman, Ottersen, Tejpar, Baral, & Fafard, 2018). In these specialised areas, scientific advice is often driven by professional expertise that is needed to meet a specific policy demand. In the context of this report, the focus is more on science advice directed towards broader policy issues that are related to multiple knowledge claims and plural values. Yet, it is always necessary to consider the context of where the advice is being used when designing the most appropriate and functional process for scientific advice for policymaking.

4.3 HEURISTICS AND FRAMES IN DEALING WITH COMPLEX AND UNCERTAIN INFORMATION

4.3.1 Cognitive heuristics and biases

Beyond the context and the specific features of each policy issue, communicating scientific results to policymakers often depends on a mutual understanding of complexity, ambiguity and uncertainty, and how these aspects are expressed in verbal or mathematical formulations. This line of research illuminates the actual decision-making processes by individuals, organisations and groups and highlights the heuristics, biases, and intuitions that lead to judgements about options or policies. Psychological research has focused on the inherent reasoning processes when facing behavioural choices. This includes the processing of information such as probabilities (Kahneman, Slovic, & Tversky, 1982), the intuitive mechanisms of making inferences (H. A. Simon, 1955, 1982), the process of dealing with cognitive stress and dissonance (Festinger, 1957) and the coping mechanisms when experiencing conflicting evidence claims or value assertions (Einhorn & Hogarth, 1981; L. Ross, 1977).

Sociological and other social science studies have been investigating the social and cultural constraints to identifying and generating options; the framing process of identifying and defining problems and procedures for their solution; norms and rules of evaluating expected outcomes within different social and cultural contexts; the perceived legitimacy of selection and evaluation schemes; and the institutional and organisational interpretations of decision-making in different cultures and political domains (Heap, Hollis, Lyons, Sugden, & Weale, 1992; Hofstede, 2003; T. B. Smith, 1977; Wagenaar, 2014).

A specific issue in the research field of human decision-making refers to strategies and heuristics of how recipients process, digest and evaluate probabilistic information and how to make sense of uncertain information in complex decision situations (overview in B. Fischhoff, 2012; Kahneman, 2011; Lockton, 2012; Tversky & Kahneman, 1974). In the context of decision and policymaking, heuristics are mental tools for coping with an abundance of information; they help individuals and groups to reduce the complexity of a decision, task or problem by focusing on specific aspects of the task or problem and ignoring others (T. Gilovich & Griffin, 2002; Kahneman, 2011). The pioneer of this research, Herbert Simon, identified several of these heuristics under the heading of 'bounded rationality' (Jaeger, Renn, Rosa, & Webler, 2001, p. 249; H. A. Simon, 1987).

Mechanisms of bounded rationality include the lexicographic methods by which individual decision-makers establish a hierarchy of the most valuable dimension (Tversky, 1972). Decision options which fail to meet the claims of the highest-ranking value (no matter how excellent their consequences are for other values) are eliminated. Another alternative is the 'satisficing' method by which individuals determine minimum thresholds for all dimensions that they care about (H. A. Simon, 1976, p. 83). Of special interest here are cognitive heuristics that may impede the understanding of scientific information for various non-scientific audiences (summary in Breakwell, 2014, p. 77). It should be stressed that these heuristics are often appropriate for dealing with everyday problems and tasks (Gigerenzer, 2008).

However, they may lead to inaccurate or inadequate inferences in cases where wicked problems and complex policy options are at stake (Lee Ross & Anderson, 1982). These are normally called 'biases' and apply not only to non-scientific audiences but also to experts, scientists, policymakers and lay audiences alike (G. Gilovich, Griffin, & Kahneman, 2002). Some of these biases, such as the tendency for over-confidence (drawing inferences from an insufficient data base), are even more frequent among experts than among other groups of society (Kahan, 2013; D. A. Moore & Healy, 2008). However, many scientific disciplines have developed methods and techniques to avoid these biases where they would lead to incoherent or inconsistent reasoning (Breakwell, 2014, pp. 79-82; Kahneman, 2011, pp. 109-197; Thaler & Sunstein, 2008, pp. 31-60).

Early psychological studies focused on personal preferences for different compositions of probabilities and outcome (risk aversion, risk neutrality and risk proneness) and attempted to explain why individuals do not base their risk judgements on expected values (i.e. the product of probability and magnitude of an adverse effect) (Pollatsek & Tversky, 1970). One of the interesting results of these investigations was the discovery of systematic patterns of probabilistic reasoning. People are risk-averse if the stakes for losses are high and risk-prone if the stakes for gains are high (Kahneman & Tversky, 1979; Tversky & Kahneman, 1981). Many people balance their risk-taking behaviour by pursuing an optimal risk strategy that does not maximise their benefits but ensures a satisfactory payoff and the avoidance of major disasters (H. A. Simon, 1972). Using rules of thumb rather than calculating expected values has been the main outcome of many empirical studies of how people perceive risks and probabilities (Boholm, 1998; Breakwell, 2014, p. 109; Covello, 1983; Sunstein, 2002, p. 37).

1. One important rule of thumb or guide is to overrate exposure and hazard rather than the probability of harm (Renn, Burns, Kasperson, Kasperson, & Slovic, 1992). Most people rate the potential for harm expressed in the number of exposed individuals, or the seriousness of the hazard in terms of energy released, or degree of toxicity, as the prime (or sometimes even only) relevant indicator for judging the magnitude of a risk, underestimating or ignoring the probability of this hazardous potential to become effective (Renn et al., 1992). If people assume an exposure above zero or believe that an agent is present that can cause harm, such as cancer, they normally conclude that any disease from which a person (exposed to this risk) suffers must have been caused by this agent (Kraus, Malmfors, & Slovic, 1992). Such assumptions imply that any exposure is regarded as being negative, irrespective of dose and exposure. For most people, it was less important to consider whether the dose of the substance or agent was low or high. Once a risk source is associated with emissions such as ionising radiation, electromagnetic fields, chemicals in air, or water pollutants, they tend to express high concern about this risk, even if the concentration is below the threshold of causing harm.

2. A second rule of thumb refers to the perception of risks and benefits. In most cases, an activity that leads to high benefits may also be associated with high risks (and vice versa). Empirical studies on how people process information about risks and benefits show the opposite effect (Gregory & Mendelsohn, 1993). For example, the intake of pharmaceuticals or dietary supplements is linked to high benefit and low risks (Alhakami & Slovic, 1994). One explanation for this high correlation between perception of risks and benefits may be

the fact that respondents calculate a crude net balance between risks and benefits. If the balance is positive, they rate the risks as low and the benefits as high, while a negative balance would result in a high perception of risks and a low perception of benefits. This adjustment process avoids painful inner conflicts to make trade-offs between risks and benefits (De Jonge, van Kleef, Frewer, & Renn, 2007). The affect heuristics operate in the same direction. The perception of risks and benefits is coloured by attitudinal strength that individuals associate with the object or topic in question (Finucane, Alhakami, Slovic, & Johnson, 2000).

3. A third rule of thumb deviates from the statistical analysis of expressing uncertainty in risk studies. The distinction that experts perform when conducting a probabilistic risk assessment (PRA) between a probability distribution and the associated degrees of remaining uncertainties (expressed in confidence intervals or in other forms of uncertainty characterisation) is not echoed in most risk perception studies (Frewer et al., 2002; Sparks & Shepherd, 1994). There is a tendency to judge a situation as either safe or unsafe, healthy or unhealthy, secure or insecure (B. Fischhoff, Slovic, & Lichtenstein, 1977). The open space between safe and unsafe is perceived as an indication of bad or incomplete science rather than an indication of (genuine) probability distributions (Renn, 2008, p. 102). The more people associate uncertainties with a scientific statement, the more they believe that there has not been enough research and that more investigations would reduce these uncertainties (De Jonge et al., 2007; Frewer et al., 2002; Sparks & Shepherd, 1994). For example, in the case of climate change, many observers are unwilling to accept the claim of an anthropogenic cause for this phenomenon since the scientists are still not 100% certain about the cause-effect relationships (E. U. Weber, 2016). The stochastic nature of relationships in the natural as well as social world remains alien to them. Notably, construal level theory (Trope & Liberman, 2010) and research on climate change (Spence, Poortinga, & Pidgeon, 2012) suggest that objects or events that are temporarily, socially and geographically distant, and uncertain (i.e. hypothetical), are evaluated as less risky and elicit less concern.

The literature includes ample evidence for the effectiveness of these biases (and others) in decision-making bodies (Festinger, 1957; Kahneman & Tversky, 1979; L. Ross, 1977; H. A. Simon, 1976, 1987) (reviews in Boholm, 1998; Breakwell, 2007, p. 78; Covello, 1983; Jungermann, Pfister, & Fischer, 2005; Kahneman, 2011). These biases are summarised in Table 2.

Bias	Description	Example
Availability	Events that come immediately to people's minds are rated as more probable than events that are of less personal importance.	Crimes by a refugee or a asylum seeker are regarded as much more prominent and problematic than done by a native citizen.
Anchoring effect	Probabilities are estimated according to the plausibility of contextual links between cause and effect, but not according to knowledge about statistical frequencies or distributions (people will 'anchor' the information that is of personal significance to them).	Toxic substances such as arsenic or mercury tend to be overrated in their potential for harm as most people associate this substance with crime and murder.
Representation	Singular events experienced in person or associated with the properties of an event are regarded as more typical than information based on frequency of occurrence.	People who have experienced a stroke of lightning tend to estimate the frequency of damage by lightning much higher than those who did not have such an experience.
Confirmation	Evidence is searched for in ways that are partial to existing beliefs, expectations, or desirable outcomes.	People sometimes select only positive information about a political candidate that one wants to support.
Motivated reasoning	Information, evidence or arguments are reframed in ways conducive to an individual's desires, needs, or goals.	Correlations between frequency of gun ownership and crime rates in different areas of the US are wrongly interpreted as evidence that gun control would not reduce crime rates.
Avoidance of cognitive dissonance	Information that challenges perceived probabilities that are already part of a belief system will be either ignored or downplayed.	People who believe that non-ionising radiation from cellular phones may cause cancer are more likely to look for sources online that confirm their view than people who do not share this belief.

Table 2. Biases (adapted and revised from Renn, 2008, p. 103).

Many of these biases and rules of thumb have also been detected and empirically confirmed in policymaking arenas (Bellé, Cantarelli, & Belardinelli, 2018; Vis, 2011). However, there are also clear indications that deviations from expert advice are less a product of ignorance or irrationality than an indication of one or several intervening context variables that often make perfect sense if seen in the light of the original context in which the individual decision-maker has learned to use them (Brehmer, 1987; Gigerenzer, 1991, 2000; Lee, 1981). Based on this situational understanding of heuristics, a different perspective on heuristics has evolved that emphasises their adaptive function to link judgement and cues from the environment (Gigerenzer, 2008). They help individuals to find quick and satisfying solutions to different and distinct environmental challenges. In this view, the information search and judgement process vary according to the structure of the concrete environment. The environment is part of the decision-maker's rationale for drawing inferences (Todd & Gigerenzer, 2012, p. 18). Uncertainty in this understanding is not a property of the knowledge system of individual decision-makers but instead emerges as a property of the mind–environment system (Kozyreva, Pleskac, Pachur, & Hertwig, 2019). Uncertainty includes both environmental unpredictability and uncertainties that stem from the mind's boundaries, such as limits in available knowledge and cognitive capabilities.

This insight from cognitive psychology is particularly relevant for scientific advice for policymakers. The more universal knowledge claims that scientific advisers are likely to bring to policymaking arenas may be incongruent with the tacit knowledge of experienced policymakers who have learned to adjust their judgements to the socio-political environment in which they operate (Jungermann, 1986). They still may benefit from knowing the scientific evidence about the topic in question, yet they may have good reasons to deviate from the implications of this evidence if they cannot apply it to their familiar environment (Woodhouse & Nieusma, 1997).

4.3.2 Technical and issue biases

Beyond the cognitive and affective heuristics that govern the processing of scientific information, the literature addresses other forms of biases that are related to interest and values that colour or even shape the evidence presented to decision-makers. It is often assumed that scientific evidence could serve as a neutral input to policymaking, as it provides unbiased and impartial factual knowledge to the decision-makers (Chalmers, 2003; Coalition for Evidence-Based Policy, 2014; Nutley et al., 2007). However, as several authors have pointed out, the implications of evidence are less straightforward when applied to wicked and contested political problems (Parkhurst, 2016, 2017). The main line of argument here is that evidence can be interpreted in different ways, depending on what parts of evidence are selected and highlighted, how ambiguity (interpretative and normative) is being addressed and selectively used, and how various interest groups will produce their own evidence to serve their own needs and positions (Parkhurst, 2016; Russell, Greenhalgh, Byrne, & McDonnell, 2008; Schön & Rein, 1994).

Parkhurst has labelled these biases as technical and issue-related:

> ***‘Creation of technically biased pieces of evidence give competing advocacy groups different pieces of conflicting evidence to justify their views or positions, undermining scientific consensus or increasing uncertainty. Biased selection and interpretation of evidence can similarly perpetuate disagreements over what the evidence actually says or means. Intractability can also arise from issue bias, however, whereby value differences between competing policy actors lead to creation or selection of evidence related to one set of goals to the exclusion of others, with appeals to ‘evidence-based policy’ serving to obscure those essential value differences’***
> (Parkhurst, 2016).

The more contested evidence is, the more it can be used as a weapon to justify different interest-driven claims (Kahan, 2013).

There is no recipe to avoid such biases. Most often, analysts believe that making policymakers aware of these biases can help them to avoid at least the most obvious fallacies (Parkhurst, 2017). Since cognitive biases are deeply entrenched and relate to unconscious mental features, Linda Alcoff (2010) concludes that is is difficult, or even impossible, to consciously correct the operation of these biases. Because of similar worries, Anderson (2012) argues that policymaking should not rely on individuals giving advice to individuals, but rather that they should be based on epistemically virtuous social institutions that provide rules and training for avoiding such biases. Some more practical orientations may be routes for overcoming some of the technical biases reported by Parkhurst and others, such as always reporting relative and absolute frequencies when reporting about statistical evidence for cause-effect relationships; providing good illustration or simulations that provide a holistic image of the phenomenon; and training decision-makers to deal with complex issues (Kahneman, 2011).

In general, mitigation strategies to overcome biases are articulated for the individual level (e.g. Fruehwald, 2017), on the organisational level (e.g. Cristofaro, 2017), on the corporate level (e.g. Otuteye & Siddiquee, 2015) and, though less frequently, on the policymaking level (Bellé et al., 2018). The advice given focuses basically on cross-checking factual claims, being especially cautious when decision options coincide with personal preferences, seeking external advice, avoiding group shifts, and monitoring expected impacts once a decision has been reached. A lot of this is close to common sense and may not be very useful for designing mitigation rules for avoiding biases in the interactions between sciences and politics. The more social and ethical biases, as pointed out by Parkhurst (2016), require institutional rules for assuring the integrity, independence and transparency of the advice mechanisms. These quality criteria for the governance of the consultation process are discussed in Section 5.7.

A more conceptual approach to dealing with potential cognitive, technical and issue-related biases has been developed by the US National Research Council. The Council members addressed the issue of heuristics and biases by recommending a combination of analytic rigour, based on comprehensive peer review, methodological robustness and deliberative argumentation among a broad representation of stakeholders and policymakers (National Research Council, 2008; P. C. Stern & Fineberg, 1996). The concept of an analytical-deliberative process supports the creation of epistemic and political robustness (Lentsch & Weingart, 2009) and suggests a policymaking process based on the inclusion of experts, stakeholders and the general public (Hajer, 2003; Hajer & Wagenaar, 2003; National Research Council, 2008; Rauschmayer & Wittmer, 2006; Renn, 2008, p. 284; Sweeney, 2004; Webler, Tuler, & Krueger, 2001). Sprain and Black (2018) have advocated a similar process that they labelled as 'deliberative enquiry'. The first element of analytical-deliberative processes refers to the inclusion of systematic and peer-reviewed knowledge. Systematic expertise is regarded as an essential resource for obtaining and utilising the background knowledge necessary to understand the complexity of wicked problems and policy issues, and to anticipate the impacts of various policy options (de Bruijn & ten Heuvelhof, 1999; Horlick-Jones, Rowe, & Walls, 2007; Klinke & Renn, 2014).

The second part of the process includes the societal debate about the issue in the policy arena. The term 'deliberation' refers to the style and procedure of exchanging arguments and reaching evidence-informed and value-balanced conclusions in a discussion (Chambers, 2003; Habermas, 1989). For a discussion to be called deliberative, it must rely on mutual exchange of arguments and reflections rather than on decision-making based on the status of the participants, sublime strategies of persuasion or socio-political pressure. Curato et al. (2017) have listed twelve major characteristics of deliberative policymaking that distinguish deliberation from bargaining and hierarchical decision-making. Furthermore, it also provides evidence that deliberation has the potential to overcome several severe decision-making problems, such as group polarisation, societal division or value pluralism. Deliberative processes include a debate about the relative weight of each argument and a transparent procedure for balancing pros and cons (Parkinson & Mansbridge, 2012; Rosa, Renn, & McCright, 2014, p. 181). Deliberation is foremost a style of exchanging arguments and coming to an agreement on the validity of statements and the applicability of values and norms. In terms of contested and complex policy issues, deliberation is required for three major tasks (Renn, 2008, p. 294):

1. First, deliberative processes are needed to define the role and relevance of the different forms and types of knowledge for making informed choices.

2. Second, deliberation is needed to find the most appropriate way of dealing with complexity, uncertainty and ambiguity and provide ample room for different interpretations of the evidence presented.

3. Third, deliberation needs to address the wider concerns of the affected groups and the public at large, particularly if the topic of the discussion is associated with high socio-political ambiguity.

The integration of analysis and deliberation is often conducted through participatory modelling, bringing policymakers and analysts together (Lang et al., 2012; Mendoza & Prabhu, 2006). This tool combines computer modelling and simulations with processing input from deliberative discussions (for example, what to model) and feeds the results of the modelling into a deliberative debate (Seidl, 2015). With both technical and social elements, participatory modelling (Daniell & Ferrand, 2006) is suggested as a means to:

- Incorporate a wide range of viewpoints and datasets;
- Assist collective decision-making processes;
- Explicate tacit knowledge, preferences and values;
- Improve legitimacy of a model;
- Promote creativity and innovation;
- Investigate individual behaviour and collective dynamics;
- Enhance individual and social learning;
- Inform and enhance collective action.

The extent to which participatory modelling can support knowledge exchange, negotiation and integration is central to its ability to support mutual understanding and social learning. This resonates with what Dreyer and Renn (2011) refer to as the evaluative potential of participatory modelling, supporting stakeholders to unpack the underlying assumptions of modelling as well as their discrete underlying belief and knowledge systems.

4.3.3 The effects of framing

Heuristics and biases are also major mechanisms that lead to a specific framing of a problem or an issue in the form of how evidence is selected and presented, and how it is embedded in a larger framework of political programmes, values or interests. A significant body of work on relations between science (broadly defined) and policy has identified the importance of frames and framing, through which particular problem definitions, knowledge claims and policy options are emphasised (considered to be 'in the frame') whilst others are effectively removed from consideration (Entman, 1993; Vreese, 2005). At any one time, the dominant framing (of an environmental problem, for example) may be so familiar as to be tacit—not consciously recognised as a means of admitting some possibilities into policy deliberations, but not others. However, framing can also be a conscious discursive strategy, as Hall (1993) found in his analysis of major changes in British macro-economic regulation. Thus:

> *'The sponsors of a frame seek to develop [it], explicate its implications for action, and establish the grounds for argument about it. They may also devise metaphors for communication of the frame ...'*
>
> (Rein & Schön, 1991, p. 275) (see also Fischer & Forester, 1993; Hajer, 1995, 2003; Hajer & Versteeg, 2005; Hajer & Wagenaar, 2003; Hisschemöller, Hoppe, Dunn, & Ravetz, 2001; Jachtenfuchs, 1996; Laws & Rein, 2003; Schön & Rein, 1994).

Just as framing helps to delimit what is 'thinkable', reframing can be a precursor for significant policy change. Hall, for example, implicates a complex form of policy learning in radical, 'third order change' (Hall, 1993, p. 279), through which established ways of thinking are superseded by a new policy paradigm. He argues that this complex process involves a shift in the interpretive framework of policy, 'embedded in the very terminology through which policymakers communicate … about their work' (Hall, 1993, p. 279). Baumgartner and Jones (1991, 1993, 2002) invoke a similar process in ascribing policy shifts in part to changes in the 'policy image' (see also Baumgartner, 2006). In their theory of 'punctuated equilibrium', Frank Baumgartner and Bryan Jones have sought to explain why policy evolution tends to be characterised by long periods of stability punctuated by intensive periods of innovation and change. They have argued that new research findings often have little impact until there is a recognition that 'something needs to be done'. Yet, in the right conditions, positive feedback can result in rapid and substantial change. Shifting 'policy images' (or frames) can contribute substantially to this process.

Frames can be changed through the interactions of competing coalitions in pluralist polities. Hajer (1993, 1995), for example, has shown how 'discourse coalitions', held together by shared 'storylines', can be significant actors in the construction of policy frames (and thereby in policy change). Interestingly, there is also evidence that advisers and advisory bodies can be important agents of learning when their work contributes to the changing of policy frames. So, for example, the UK Royal Commission on Environmental Pollution's (RCEP's) trademark style of 'interdisciplinary deliberation' encouraged 'frame-reflection' (Rein & Schön, 1991, p. 286), in a number of its most influential studies (Owens, 2015, p. 148). An interesting case in point was its study of energy and climate change (Royal Commission on Environmental Pollution, 2000), in which it framed an already widely-debated topic in a novel and compelling way, such that government was able to accept and implement its radical recommendations on long-term reductions in carbon dioxide emissions in the UK. More generally, as Owens (2015, p. 150) found in her long-term study of the RCEP:

> ***'the rigorous testing and challenging of ideas enabled the members not only to 'bottom-out' their enquiries through interrogation of the issues at hand but also, in prominent cases, to re-frame the questions, open up novel policy approaches, and stimulate learning in wider policy communities'.***

The issue of frames and framing touches on an interesting, broader dilemma for those considering how best to design science advisory processes in a policy context. Advice needs to be meaningful in the 'real world' — the world as it is now — but there is also clear evidence that advice can serve a vital function when it challenges dominant policy frames — especially when advisers are in a position to present such a challenge consistently and over an extended period of time.

4.4 COMMUNICATING SCIENCE AND UNCERTAINTY

In accordance with Burns, O'Connor and Stocklmayer (2003), science communication is defined as:

> *'the use of appropriate skills, media, activities, and dialogue to produce one or more of the following personal responses to science… awareness, enjoyment, interest, opinion-forming, and understanding'.*

This definition stresses the products of communication. In addition, it is essential to focus on the organisational structure of communication. There is a clear agreement among communication analysts that two-way communication, based on dialogues and interactions, is usually more effective and provides more opportunities for shared meaning than one-way communication (Centers for Disease Control and Prevention, 2014, p. 7; Mulligan, McCoy, & Griffiths, 1998; National Research Council, 1989; Organisation for Economic Co-operation and Development, 2002).

Effective communication is also important for the dialogue between science advisers and policymakers. Uninformed decision-making can harm people. It can encourage policymakers to prioritise less effective actions, lead them to waste money, and has many other undesirable consequences. Moreover, since all science is imbued with uncertainty, it would come close to lying to pretend that this uncertainty does not exist. When science and uncertainty communication works well as it should, it helps people to make sense of science and make sound choices. Baruch Fischhoff (2013) has formulated the governing idea in one sentence:

> *'The goal of science communication is not agreement, but fewer, better disagreements'.*

Yet how should this be done?

The science of science and uncertainty communication gives some clear answers. It is vital that science advisers remain keenly alert to the needs of those with whom they are communicating, that they listen. What decisions are to be taken, and why? Identifying the relevant decisions, they can see what the decision-makers know and also what they do not know. This helps the advisers to identify the science that is relevant to the choices to be made. In this way, the scientist can find out what the decision-maker thinks he or she knows, point to beliefs that contradict scientific evidence, identify and fill knowledge gaps, and honestly tell the decision-maker what is not known.

The final step in this process is to evaluate the adequacy of the communication strategy, to check that it is fit for purpose. The science of science communication has taught us that there is not a one-size-fits-all way of communicating science and uncertainty. What are needed are customised communication strategies and decision-tailored designs (see B. Fischhoff, 2013; B. Fischhoff & Davis, 2014).

What is known in communication science about effective ways of communicating evidence to policy and decision-makers? The answer to this question depends on the type of decision that policymakers are facing. It is essential to focus on three main types of decision:

- When is it time to act?
- What are the options?
- And which is the best option?

Each of these questions requires its own communication strategy. The uncertainties most relevant to the particular decision problem will need to be identified and assessed. They must then be communicated — and communicated in a way that it gives the decision-maker the science and knowledge background that he or she needs to make a well-informed choice. Detailed protocols promoting good science and uncertainty communication describe how this can be done (B. Fischhoff & Davis, 2014). To make sense of science, new communication tools and procedures are not required. It is sufficient to use the tools and techniques that are already in place.

There is always a risk that communicating about science and uncertainty will lead to distrust. It has been shown that 'distrust, once initiated, tends to reinforce and perpetuate distrust' (Slovic, 1999). Here, honesty is the key. Sadly, there are too many examples of inefficacious science and poor uncertainty communication. Some communication strategies have slowed down research or even stigmatised an entire research field. Decision-making and risk management both involve two equally important components: information (knowledge) and preferences (values). Science can give decision-makers the background knowledge and information they are looking for, but scientists should avoid persuasion and resist the temptation to convert the decision-maker to their own values and preferences. Failure to do this is likely to create stigmatisation and mistrust. However, at a more general level, one cannot make sense of science without a shared and well-communicated conception of the common values at stake, and of course, the value conflicts contained therein. Making sense of science is also a matter of making sense of the values that matter to all parties involved.

A specific problem is the communication of uncertainty. Systematic approaches for identifying and describing uncertainties, such as those described in the preceding sections, are necessary for providing good scientific advice and should be a routine part of best practice. Communicating information on uncertainty to non-technical audiences poses a number of challenges. For example, multiple studies have demonstrated that verbal expressions of probability or likelihood are interpreted in different ways by different people (Budescu, Por, Broomell, & Smithson, 2014; Theil, 2002). Variable interpretation of verbal terms can be reduced by presenting them together with numerical probabilities (Budescu et al., 2014) and reduced further still, though not removed, if the numerical probability is presented before the verbal expression rather than afterwards (Jenkins, Harris, & Lark, 2018). Studies on the communication of numerical ranges representing uncertainty have shown that a small but non-negligible proportion of people focus on one end or other of the range (e.g. Dieckmann, Peters, & Gregory, 2015).

The effectiveness of graphical formats, such as box plots and histograms or probability density functions, has been studied by various authors (e.g. J. A. Edwards, Snyder, Allen, Makinson, & Hamby, 2012; Ibrekk & Morgan, 1987). However, some of these formats are often used to represent variability rather than uncertainty, which may lead to misinterpretation. For example, after finding that people tended to focus on one end of error bars representing uncertainty about maximum or minimum temperatures, Savelli and Joslyn (2013) suggested this was caused by interpreting the bar as representing diurnal variation rather than uncertainty. Similar problems may be expected with numerical probabilities, since these are also often used to express variability rather than uncertainty. For this reason, EFSA (2019) has proposed to present probabilities which quantify uncertainty as '% certainty' when communicating scientific assessments.

There is a body of literature that recommends communicating with frequencies rather than probabilities (e.g. Gigerenzer, Gaissmaier, Kurz-Milcke, Schwartz, & Woloshin, 2007). However, Joslyn and Nichols (2009) point out that many of the studies in that literature required subjects to estimate probabilities in complex tasks involving base rates or the conjunction of more than one probabilistic event. They argue that this is a fundamentally different cognitive task from that required in a situation where a probability representing uncertainty of an event or outcome is provided to the audience, as would occur when using probability to express the likelihood of a scientific conclusion being correct. Joslyn and Nichols (2009) report an experiment in which uncertainty of forecast wind speed was provided to subjects in either frequency or probability format, and the latter was better understood. Further studies are needed to confirm whether this would occur in contexts other than weather forecasts.

Spiegelhalter (2017) reviewed a wide range of techniques used to communicate risk and uncertainty information. He reported that only tentative conclusions could be drawn, and offered tentative recommendations on general issues, the communication of numerical risks, and visualisations. Similarly, EFSA (2019) found that the available experimental evidence on communication of uncertainty was limited, and additional reasoning was needed to develop practical guidance. They concluded that further research would be needed to evaluate the performance of the approaches they recommend, and to refine them in future where needed. Another aspect is the dependence on context. Fischhoff (2009; 2013) has emphasised the need for testing the communication strategies for each context in which they are used. One cannot assume that a communication strategy that works in one context will also work for other contests. The impacts of communication need to be tested in each case. Poor risk communication can lead to poor decision-making. In many situations, e.g. in medicine, risk and uncertainty communication strategies can be so important that it would be immoral not to test them before they are employed.

Evidence on how to communicate complexity, uncertainty and ambiguity has been mainly collected for communication between scientists and various lay audiences. However, there are also publications that address the communication between science and policymaking. As stated in the Commission's Communication on the Precautionary Principle (European Commission, 2000):

> ***'Decision-makers need to be aware of the degree of uncertainty attached to the results of the evaluation of the available scientific information'.***

Providing this awareness requires scientists to identify the many sources of uncertainty that affect any evaluation and assess how they feed through the scientific reasoning that leads to the conclusions. These activities should therefore be an integral part of the scientific process. This is reflected in an European Commission Communication (2000), which requires:

> ***'A scientific evaluation, as complete as possible, and where possible, identifying at each stage the degree of scientific uncertainty.'***

Similarly, the Codex Working Principles for Risk Analysis (Food and Agriculture Organization of the United Nations & World Health Organization, 2018, originally published in 2003) states:

> ***'Constraints, uncertainties and assumptions having an impact on the risk assessment should be explicitly considered at each step in the risk assessment and documented in a transparent manner. Expression of uncertainty or variability in risk estimates may be qualitative or quantitative, but should be quantified to the extent that is scientifically achievable.'***

It is important to consider in which instances quantification is superior to verbal expressions of uncertainty and under what circumstances quantification is scientifically achievable and justifiable. In many publications, the impact of uncertainties is expressed by verbal descriptions of uncertainty distributions. Words such as 'likely', 'unlikely', 'may' or 'possible' are often perceived as ambiguous and interpreted in different ways by different individuals (e.g. Budescu et al., 2014; Theil, 2002). Therefore, when such expressions are used, policymakers may misunderstand the degree of uncertainty that scientists intend to convey. This linguistic ambiguity can be avoided by quantifying uncertainty using subjective probability, since subjective (Bayesian) probabilities have defined meaning based on the operational framework established by Ramsey (1926), de Finetti (1937) and

Savage (1954). Other quantitative representations of uncertainty, such as fuzzy sets and degrees of possibility, lack defined meaning and are much less used in practice as indicated, for example, by Cooke's (2015) analysis of the frequency of these terms and 'Bayes' in the field of artificial intelligence.

However, as recognised by Codex (Food and Agriculture Organization of the United Nations & World Health Organization, 2018), quantification of uncertainty is neither always achievable, nor desirable. First, the operational framework for using probability to quantify uncertainty applies only for well-defined outcomes or estimates. This may appear to limit the use of probability to assessments of well-defined problems. However, probability may also be applicable to *parts* of more complex or ambiguous problems, if they can be framed as well-defined sub-questions. For example, assessing the risks and benefits of stem cell therapies is a complex problem, involving ambiguity, value uncertainty and ethical questions (Sahlin, Persson, & Vareman, 2011). However, Sahlin et al. identify some potential risks and benefits for which there is at least some useful evidence, and uncertainty about these could be expressed using subjective probability, if they could be framed in a well-defined manner (e.g. the probability that a specified therapy in specified conditions will cause a specified type of adverse or beneficial effect). Using subjective probability for those parts of the problem where quantification is possible might make a useful contribution to informing the wider analytic/deliberative process, with other, more complex or ambiguous aspects of the problem being addressed qualitatively. It is crucial, however, that policymakers understand the rationale behind subjective probability estimates and know how to interpret their validity.

A second consideration is whether it is necessary to take account of epistemic uncertainty of subjective probabilities. This is a contested issue. Subjective Bayesians would argue that, in principle, a person could express their uncertainty for any well-defined question as a precise probability, while accepting that in practice they would be indifferent to small changes in probability (e.g. O'Hagan, 1988). However, others point out that the epistemic basis for the same subjective probability varies between questions, e.g. a probability of 0.5 for a toss of a fair coin has a different quality from a probability of 0.5 for 'rain tomorrow', which needs to be expressed. This can be done quantitatively, using higher order probabilities (probabilities of probabilities) (Sahlin, 1993) or imprecise probabilities (ranges for probabilities) (Walley, 1991). It can also be done qualitatively, e.g. by accompanying the subjective probability with a qualitative expression of the assessors' degree of confidence in their assessment of that probability (Spiegelhalter, 2017).

The Intergovernmental Panel on Climate Change (IPCC) uses a combination of these approaches to express uncertainty in their assessments. A guidance note for authors of their 4th Assessment Report (Intergovernmental Panel on Climate Change, 2005) provided two scales of qualitative terms with quantitative definitions: a scale for the level of confidence in a model, analysis or statement, defined in terms of the chance of being correct (e.g. 'High confidence' = 'About 8 out of 10 chance'); and a scale for the likelihood of an outcome occurring, defined by probability ranges (e.g. 'Likely' = '>66% probability'). Following external criticism and an independent review (Inter Academy Council, 2010), IPCC published a revised guidance note for authors of their Fifth Assessment Report (Mastrandrea et al., 2010). This retained the quantitatively-defined scale for likelihood from IPCC (2005) but replaced the quantitatively-defined scale for confidence with a qualitative scale with 5 categories (from 'very low' to 'very high'), based on qualitative evaluation of 'evidence' (limited, medium or robust) and 'agreement' (low, medium or high). Mastrandrea et al. recommend that their quantitatively-defined likelihood scale be used only when there is robust evidence and/or high agreement between experts.

Mastrandrea et al.'s approach was applied in the 5th Assessment Report of the IPCC (2014) and also in the more recent Special Report (Intergovernmental Panel on Climate Change 2018). For example, the Special Report includes the conclusion that 'Global warming is likely to reach 1.5°C between 2030 and 2052 if it continues to increase at the current rate (high confidence)'. The terms 'likely' and 'high confidence' are shown in italics and 'likely' is defined in a footnote on a different page as corresponding to 66-100% probability. Multiple studies (e.g. Budescu et al., 2014) have shown that people interpret the IPCC's verbal likelihood terms in different ways, as for other qualitative expression, but that this problem can be reduced by presenting the verbal and numerical expressions together (e.g. 'likely (66-100% probability)').

In contrast to the guidance of Mastrandrea et al. (2010), Morgan et al. (2009) assert that all states of evidence and agreement can in principle be expressed using subjective probabilities, so long as the question to be addressed is well-defined. The theoretical justification for this is provided by the work of Ramsey (1926), de Finetti (1937) and Savage (1954). More recent guidance published by the EFSA (2018b, 2018c) takes the same view, and proposes a modified version of the IPCC likelihood scale with non-overlapping probability ranges and flexibility for assessors to use multiple ranges or specify non-standard ranges to express their probability judgements (European Food Safety Authority, 2018b, 2018c).

However, the EFSA guidance also recognises that, even when a question is well-defined, assessors may nevertheless feel unable to give any range of probabilities narrower than 0-100%. In such cases, it may be misleading to give a qualitative expression of likelihood or confidence, since policymakers and others might interpret this as corresponding to some range of probabilities narrower than 0-100%. Instead, EFSA (2018b, 2018c) recommends that assessors report that the answer to the question or sub-question is inconclusive and the probability unknown, and provide instead a qualitative description of the cause and nature of the uncertainties involved. This can be done in many ways, from an informal narrative description to a structured characterisation using one or more ordinal scales, such as the pedigree criteria of the NUSAP approach (see Chapter 5).

Thus, both the IPCC approach (Mastrandrea et al., 2010) and EFSA (2018b, 2018c) respect the need to acknowledge when quantification is not possible and what is simply unknown, as emphasised in other publications on scientific uncertainty (e.g. Stirling, 2010). In addition, both emphasise that all plausible sources of uncertainty should be taken into account and both emphasise the need to provide a traceable account of the evidence and reasoning for the expert judgements involved. Therefore, both can potentially contribute to a "Socratic approach" in which assessors aim to honestly express their epistemic uncertainty, without pretending that their knowledge and information is more precise or better than it is (Sahlin et al., 2011).

On a more general level, the guidelines by the German Federal Institute for Risk Assessment (BfR) undertook a major literature study to derive the most important lessons for communicating complex and uncertain information from the scientists of the risk assessment agency to policymakers in ministries and other agencies. They adopted the following conclusions (Federal Institute for Risk Assessment, 2007, p. 30, not verbally cited but slightly adapted for this document):

- Transparency: The communicating science advisers structure the material in a transparent, logical manner.
- Data quality: The communicating science advisers provide information on the quality of the data stock (topicality, scientific validity, statistical reliability, relevance for the questions in hand) and how the available data have been incorporated into the assessments, evaluations, interpretations or conclusions. They also provide clear information about the nature and structure of the remaining uncertainties.
- Competence boundaries: The science advisers draw attention to the existing boundaries of the available scientific findings and experiences and the boundaries of statutory provisions, as well as to their own competence in assessments, evaluations, interpretations or conclusions (including ambiguities).
- Remaining uncertainties: The science advisers indicate the degree of remaining uncertainties and explain them for the later stages of designing policy choices. In particular, they outline:
  - Suspected random and systematic measurement mistakes, uncertainties in the scope of data extrapolation.
  - Remaining uncertainties concerning the power of the models used.
  - The system limits to the observed situations.
  - Suspicion about other, as yet unknown, causal relationships that may play a role for understanding the phenomenon.
- Evidence used: The science advisers reveal which situations, scientific findings, experiences, assumptions or presumptions lead or have led to which assessments, evaluations, interpretations or conclusions.
- Rationale: The communication only includes those conclusions which are either (a) comprehensible (in themselves) without further explanation because

of already generally recognised rules for the submission of proof or direct empirical evidence, or (b) which can be justified because of the plausible derivation of a chain of thoughts, taking into account all assumptions and the conventions agreed by the scientific community.

- Opposing views: The science advisers indicate any opposing scientific views and how deviating evaluations, assessments, interpretations or conclusions are justified there. In particular, they specify the assumptions that underlie different interpretations.
- Inter-subjective validation: The contents of communication are 'inter-subjective', as far as possible, i.e. another group of analysts would come to the same conclusions when looking at the same available scientific findings and experience and when basing their work on comparable assumptions or presumptions.

The approaches outlined above can be applied to scientific advice in many contexts and can be scaled to the time and resources available, including urgent assessments (European Food Safety Authority, 2018b). When applied well, they should improve the rigour of uncertainty assessment and reduce ambiguity in expressing uncertainty and hence provide a more useful contribution to decision-making processes.

Chapter 5: The potential for improving the use of scientific advice for policymaking

5.1 TRANSLATING SCIENTIFIC EVIDENCE INTO POLICY-RELEVANT SCIENCE ADVICE

The science advisory ecosystem consists of many potential elements. There are a large number of possible players including individual academics, universities, research institutes, academic societies, professional bodies, government employed practising scientists, scientists within policy agencies, scientists within regulatory agencies, independent think-tanks, 'what works' units, national academies, government advisory boards, science councils, science advisers to executive of government, parliamentary libraries and parliamentary advice units. Different roles played in a science advisory ecosystem include knowledge generation, knowledge sysnthesis, knowledge broking and policy evaluation (Gluckman, 2018). The nature of scientific advice ranges from policy for science, to evidence for policy options, to evidence for policy implementation, to evidence for policy evaluation, to scenario analysis and horizon scanning, to crises (Gluckman, 2018).

As Gluckman (2016) noted, policymaking is a messy process in which scientific evidence is only one of many inputs. The process is often best characterised as "muddling through" rather than as a meticulously designed procedure (Forester, 1984; Lindblom, 1959; Parsons, 2002). The issues for which scientific input are most needed by policymakers are the very ones for which the science is often the most complex, multidisciplinary and incomplete. Science and policymaking are different realms characterised by very different cultures, styles of reasoning, methods and epistemologies. The policymaker wants relevant knowledge. However, it is not easy to define what the relevant knowledge is, and this often requires a long and ongoing dialogue between science, policy and other societal actors (Clark, van Kerkhoff, Lebel, & Gallopin, 2016).

There is a need to reduce complexity, to confine the problem into a choice between various policy options. As many of the issues where scientific advice is needed are pressing and urgent, solutions need to be found within a certain timeframe (Gee et al., 2013). Often, this is part of a conflict between policymaking and science. There is a need to explore possibilities, to balance pros and cons, and instruments are needed to do so. There is a need to legitimise decisions within an arena of competing different interest groups and a need for robustness and, where possible, consensus in the assessments (van der Sluijs, 2010). Assessors working at the interface between science and governance have to negotiate credibility with scientific peer groups, policymakers and other actors involved (van der Sluijs, 1997).

In the past, it was generally assumed that science and democracy worked harmoniously in the pursuit of the common good. This started to change in the early 1960s, with President Eisenhower's (Eisenhower, 1961) warning about the risk that public policy could be hijacked by a techno-scientific elite. There has been a major shift in recent decades from an advisory model based on technocracy, first to models that follow a decisionistic divide between science and policymakers ('truth speaks to power'), and then to more pragmatic and deliberative forms of advice today (Forester, 1999; Habermas, 1966; Weingart, 2002). More recently, a growing number of controversial technical solutions have been implemented to manage value and political questions (for instance, algorithms for police profiling and court cases). Finally, the deployment of techno-science to influence the outcome of political processes (social networks), and to alter aspects of the human condition (gene-edited babies) without proper deliberation and democratic control has increased the risk of conflict between the two sources of legitimisation of the modern state (Noto La Diega, 2018).

The interaction between knowledge and decision-making is complex and often non-linear (The Social Learning Group, 2001). It is not just a matter of translating scientific evidence into policy-relevant science advice. Knowledge always informs action in some way and action, together with its associated interests and agency, always structures knowledge (The Social Learning Group, 2001). The initiative to put issues that require science advice on the societal and policy agendas can come from many different societal actors, ranging from scientists to citizens, NGOs, watchdogs, investigative journalism, industry, interest groups etc. For instance, evidence that gives grounds for concern about health or environmental risks could come from the public and be subsequently taken up by researchers. Indeed, sometimes, history has showed that lay people were right and experts wrong (e.g. in the Love Canal controversy on health of residents living on a former chemical waste disposal site (Fjelland, 2016)); for more examples, see the Late Lessons from Early Warnings reports (European Environment Agency, 2001, 2013).

In other cases, such as climate change and ozone depletion, concerns that began in the scientific community later started to interact with the policymaker community (The Social Learning Group, 2001). In the latter case, during the long periods — sometimes several decades — before the issues were taken up on the policy agenda, 'knowledge-intensive' and 'action-intensive' functions of risk management were largely disconnected. Risks such as climate change, ozone depletion and acid rain were largely treated as scientific issues, with any goals for management action posed in general terms more likely to be shaped by debates in other issue areas (and reflecting other agendas) than by any close reading of the state of the science (The Social Learning Group, 2001).

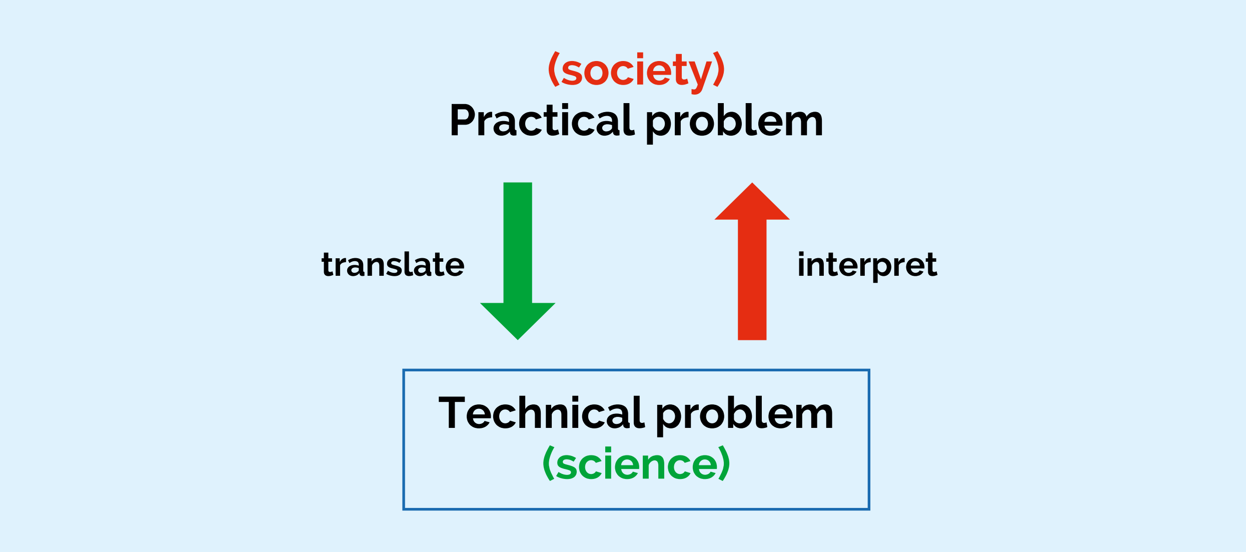

Fig. 1. Practical and technical problems (Ravetz, 1971)

At the interface between science and policy, scientists translate practical problems into one or more technical problems that can be addressed by science (Ravetz, 1971; Fig. 1) . Practical problems are defined in terms of ultimate purposes such as human welfare or healthy ecosystems. Technical problems are defined in terms of specifications (Strand, 2002), for instance, growth quantified in GNP (gross national product) or biodiversity trends quantified by the Red List Index of endangered and vulnerable species. Many aspects of the original problem are lost in translation and this unavoidable reduction of a complex reality can be done in many different ways, each having their own strengths and limitations (e.g. Schön & Rein, 1994). In the end, the translation of any policy question into a particular technical problem that scientists can address is a matter of choice, not a matter of fact (Strand, 2002).

In bridging science and policy, one must be aware that the scientific evidence relates primarily to the technical problem, which may not encompass all relevant aspects of the actual (complex) policy issue for which we seek technical advice (Hisschemöller et al., 2001). The degree to which it also relates to the policy problem is limited by the imperfections in the steps of translation (reduction of complexity, uncertainty and ambiguity about what the relevant aspects of the problem are, etc.) and the imperfections in the step of interpretation: how can the evidence help solve the practical (policy) problem (Hisschemöller et al., 2001). The steps of translation and interpretation are craft skills. These steps are outside the domain of science and no scientific methods exist to complete these steps, but they are essential and inescapable at the science-policy interface (Ravetz, 1971).

Note that Figure 1 is an idealised representation. In reality, the processes are non-linear and iterative, and the translation into technical problems is more often implicit (in sticky or dominant problem frames that are taken for granted without any critical reflection) than explicit. Conceptualising this process in terms of translation and interpretation between practical and technical problems helps to critically reflect on these processes, identify and open up important framing assumptions, and reflect more systematically on the potential mismatches between technical and practical problems (e.g. Delgado & Strand, 2010).

For instance, relevant knowledge is generally much broader than the often highly technicalised problem frames suggest. It is increasingly recognised that humans play a central role in the complex societal challenges that we are facing today. These cannot be explained by physical, environmental and biological causes alone. Understanding the human factor requires knowledge about the historical, cultural and communication processes in which human life is embedded. This is why arts and humanities research should be an all-encompassing component in addressing complex challenges at the science-policy interface (Science Europe Humanities Comittee, 2013).

To quality-control the craft-skill of translating practical into technical problems, the concept of context validation (Dunn, 2001) is key. Context validity refers to the validity of inferences that we have estimated the proximal range of rival problem framings of a given public policy problem, before an assessment is carried out and/or a solution is chosen. The information used in decision-making should cover the complete set of relevant knowledge present in a particular policy context (Dunn, 2001). In other words, the scope of the knowledge considered, as well as the set of rival possible framings of the issue, must be broadened in order to minimise the possibility that important aspects of the problem are overlooked. This is necessary to avoid so-called type III errors, where the wrong problem (or a too narrow set of technical problems) is being assessed.

Based on Watson (2005) — Chair of the Intergovernmental science-policy Platform on Biodiversity and Ecosystem Services (IPBES) — for a scientific assessment to be useful, it has to have the following characteristics:

- It must involve experts from all relevant disciplines and stakeholder groups in the scoping, preparation, peer-review and outreach/communication;
- The process must be open, transparent, representative and legitimate;
- The process should incorporate institutional as well as local and indigenous knowledge whenever appropriate (see also Hulme (2011), who stresses that for biodiversity and eco-systems services assessments we should move beyond conventional scientific knowledge assessments that legitimise, almost exclusively, only peer-reviewed material. Knowledge established across all scales, especially local and indigenous knowledge, and knowledge validated in multiple ways, must be eligible for inclusion);
- The results and analyses need to be technically accurate;
- The results and analyses need to be policy-relevant but not policy-prescriptive — providing options, not recommendations;
- Plausible scenarios of the future should be relevant for policy formulation over a range of spatial scales from local to regional and global;

- The conclusions must be evidence-based and devoid of conflicts of interests. However, it should be recognised that the assessment conclusions will be used within in a range of value systems and in an arena of competing interest;
- It must cover risk assessment, management and communication;
- It must present different points of view, and characterise — and where possible quantify — the uncertainties involved.

A study by Cash at al. (2003) suggests that efforts to mobilise science and technology for sustainability are more likely to be effective when they manage boundaries between knowledge and action in ways that simultaneously enhance the salience, credibility and legitimacy of the information they produce. Effective systems apply a variety of institutional mechanisms that facilitate communication, translation and mediation across boundaries.

5.2 WICKED PROBLEMS, POST-NORMAL SCIENCE AND KNOWLEDGE QUALITY ASSESSMENT

Where social scientists long ago coined the term 'wicked problems' (Rittel & Webber, 1973) for issues characterised by perpetual controversy (in contrast to 'tame', soluble problems, as in puzzle-solving), natural scientists tend to formulate new research projects based on the implicit assumption (and explicit promise) that uncertainty will be reduced and controversy will be resolved (van der Sluijs, 2005). Often, by the end of such projects, the uncertainties have actually increased (van der Sluijs, 2005, 2010, 2012), a paradox described by climate scientist and IPCC lead author Kevin Trenberth (2010) as 'more knowledge, less certainty'. Sarewitz's (2004) seminal paper *How science makes environmental controversies worse* further shows that more and better science will not close the societal controversies (cf. Collingridge & Reeve, 1986). This paradox stems from a mismatch between the theory of knowledge implicitly assumed in scientific assessments of such risks, and the wicked characteristics of this class of problems, which Bremer (2013) summarised as:

1. Differing degrees of uncertainty (or indeed complete ignorance) associated with the issue;
2. A lack of consensus on the definition of the issue and its most appropriate 'solution', owing to a plurality of legitimate yet intractable perspectives within society;
3. The governing system as a complex network of political interactions between stakeholders, pressured by urgency and high stakes.

A similar analysis is made by the EU COST action *Expert Judgement Network: Bridging the Gap between Scientific Uncertainty and Evidence-Based Decision Making* (COST Action IS1304, 2019). The action responds to the major gap between the science models relevant for cutting-edge research and those required for policy analysis and advice. For instance, science-based models often involve substantial uncertainty which require explicit and timely characterisation. However, the shortage and cost of timely empirical data inevitably require expert judgement. How such judgement is best elicited is critical to a decision process, as differences in the robustness of elicitation methods can be substantial and require careful consideration of a range of well-known biases and pitfalls, as we discussed in Section 4.3.

This mismatch highlights the urgent need for a new approach to issues that are characterised by deep uncertainty, high systems complexity and a highly polarised societal context. For the governance of complex risks, the 'modern model' of scientific knowledge as perfection, determinism, and predictability (speaking truth to power) (Collingridge & Reeve, 1986; Wildavsky, 1979) is increasingly untenable and unfit. This mismatch promotes paralysis, an infinite loop of demand for more research and sustained doubt on whether the limited state of knowledge can justify any interventions (Harremoës, Gee, & Macgarvin, 2001). In view of complexity and deep uncertainty, the modern model needs to be replaced by a model of pluralistic knowledge production, aiming at enhancement of the quality and relevance of knowledge for policy, while fully acknowledging pluralism of relevant views of reality, complexity, and incompleteness of our understanding (working deliberatively within imperfections) (Funtowicz & Ravetz, 1993; van der Sluijs, 2012; Verweij & Thompson, 2006).

As has been stated in Chapter 3, this call for pluralistic knowledge input should not be seen as an invitation for arbitrariness in creating and presenting evidence. In addition, society's capacity to tolerate uncertainty can be enhanced by increasing resilience (Resilience Alliance, 2010). The major mechanisms of rigorous review and methodological soundness also apply to the analysis of wicked problems, but, due to complexity, uncertainty and ambiguity, there will be more than one adequate and scientifically-substantiated interpretation of what the evidence is and what it means for society (Funtowicz & Ravetz, 1993).

Funtowicz and Ravetz (1993) have called this class of problems post-normal, where 'normal' refers to Kuhn's (1962) concept of normal science. Kuhn describes normal science both as 'a strenuous and devoted attempt to force nature into the conceptual boxes supplied by professional education' (Kuhn, 1962, p. 5) and as the practice of uncritical puzzle-solving within an unquestioned framework or 'paradigm'. Funtowicz and Ravetz (1993) signalled that such a normal science approach runs into serious limitations when addressing societal issues (at that time, nuclear reactor safety), where scientific evidence is highly contested and plagued by uncertainties while decision stakes are high and values are in dispute. The available knowledge bases are typically characterised by imperfect understanding of the complex systems involved (Ravetz, 1987). Models, scenarios, and assumptions dominate assessment of these problems and many (hidden) value loadings reside in problem frames, indicators chosen and assumptions made (Kloprogge, van der Sluijs, & Petersen, 2011). Scientific assessments of complex risks are thus unavoidably based on a mixture of knowledge, assumptions, models, scenarios, extrapolations, and known and unknown unknowns. Consequently, scientific assessments will unavoidably use expert judgements (van der Sluijs et al., 2005). They comprise bits and pieces of knowledge that differ in status, covering the entire spectrum from well-established knowledge to judgements, educated guesses, tentative assumptions and even crude speculations (Funtowicz & Ravetz, 1990; van der Sluijs, 2012; van der Sluijs et al., 2005; van der Sluijs et al., 2008). Knowledge utilisation for governance of complex issues requires a full and public awareness of the various sorts of uncertainty and underlying assumptions.

Post-normal science (PNS) is both a critical concept and an inspiration for a new style of research practice. Its dichotomous nature can be described as both descriptive (describing urgent decision problems — post-normal issues — characterised by incomplete, uncertain or contested knowledge and high decision stakes and how these characteristics change the relationship between science and governance) and normative (proposing a style of scientific enquiry and practice that is reflexive, inclusive and transparent regarding scientific uncertainty, and that moves towards democratisation of expertise) (Strand, 2017). It is based on three defining features (Funtowicz & Ravetz, 1993; A. C. Petersen, Cath, Hage, Kunseler, & van der Sluijs, 2011):

- The management of uncertainty. Post-normal science acknowledges that uncertainty is more than a number-range. Ambiguous knowledge assumptions and ignorance give rise to deep uncertainties;
- The acknowledgement of a plurality of legitimate perspectives — both cognitive and social. Complex problem-solving requires interdisciplinary teamwork, including expertise from outside science (NGOs, stakeholders, citizens). Scientists from different backgrounds often have irreconcilable and conflicting, yet tenable and legitimate scientific interpretations of the same body of evidence;
- The management of quality. An extended peer community includes representatives from social, political and economic domains who openly discuss various dimensions of uncertainties, strengths, weaknesses and ambiguities in the available body of scientific evidence and its implications for all stakeholders with respect to the issue at hand.

In a post-normal approach, the normal task in science of fact-finding is still regarded as necessary, but no longer as fully feasible nor as sufficient for the interface between science and policy (van der Sluijs, 2012). It needs to be complemented by the task of exploring the relevance of deep uncertainty and ignorance that limit our ability to establish objective, reliable and valid facts. To perform this task, Knowledge Quality Assessment (KQA) tools are central in post-normal science (Clark & Majone, 1985; Funtowicz & Ravetz, 1990; Kloprogge et al., 2011; Maxim & van der Sluijs, 2011, 2014; Refsgaard, van der Sluijs, Brown, & van Der Keur, 2006; Refsgaard, van der Sluijs, Højberg, & Vanrolleghem, 2007; Saltelli et al., 2008; van der Sluijs et al., 2005; van der Sluijs et al., 2008; Walker et al., 2003). These tools seek to systematically reflect on the limits of knowledge in relation to its fitness for function. It comprises systematic analysis of, and critical reflection on, uncertainty, assumptions and dissent in scientific assessments in their societal and institutional contexts (Haque, Bremer, Aziz, & van der Sluijs, 2017; van der Sluijs et al., 2008).

A similar notion comes from Gibbons et al. (1994), who coined the notion of Mode 2 knowledge production that is socially distributed (see also Section 3.3). While Mode 1 knowledge production used to be located primarily at scientific institutions (universities, government institutes and industrial research labs) and structured by scientific disciplines, its new locations, practices and principles are much more heterogeneous. Mode 2 yields 'socially robust knowledge', which has a different epistemological status from Mode 1 science (Nowotny et al., 2001). As summarised by Hessels and Van Lente (2008), Mode 2 knowledge production differs from Mode 1 in five characteristics:

- Mode 2 knowledge is generated in an applied context. Mode 1 knowledge can also result in practical applications, but these are always separated in space and time from the actual knowledge production. This gap requires a so-called knowledge transfer. In Mode 2, such a distinction does not exist.
- Mode 2 is transdisciplinary, which refers to the mobilisation of a range of theoretical perspectives and practical methodologies to solve problems. Transdisciplinarity goes beyond interdisciplinarity, in the sense that the interaction of scientific disciplines is much more dynamic and research results are more diffuse (to problem contexts and practitioners) during the process of knowledge production.
- Mode 2 knowledge is produced in a diverse variety of organisations, resulting in a very heterogeneous practice. The range of potential sites for knowledge generation includes not only traditional universities, institutes and industrial labs, but also research centres, government agencies, think-tanks, high-tech spin-off companies and consultancies. These sites are linked through networks of communication and research is conducted in mutual interaction.
- Mode 2 knowledge is based on reflexivity; it is primarily a dialogic process and has the capacity to incorporate multiple views. This relates to researchers becoming more aware of the societal consequences of their work ('social accountability'). Sensitivity to the impact of the research is built in from the start.
- Mode 2 comes with novel forms of quality control. Traditional discipline-based peer review systems are supplemented by additional criteria of an economic, political, social or cultural nature. Due to the wider set of quality criteria, it becomes more difficult to determine 'good science', since this no longer is limited to the judgement of disciplinary peers. However, this does not imply that Mode 2 research is generally of a lower standard.

5.3 GUIDELINES FOR INTEGRATING UNCERTAINTY INTO POLICY ADVICE

Two particular strategies to deal with uncertainty have dominated current practices of science for policy: uncertainties are either downplayed to promote radical risk mitigation policies (enforced consensus/overselling certainty), or they are over-emphasised to prevent government intervention in the economy (van der Sluijs et al., 2010). Both promote policy strategies that can result in extreme error-costs for society (van der Sluijs et al., 2010). More sophisticated strategies to deal with uncertainty are emerging (van der Sluijs et al., 2010).

Without pretending to be complete, we discuss three illustrative state-of-the-art approaches to dealing with uncertainty at the science-policy interface: The Guidance approach of the Netherlands Environmental Assessment Agency (A. C. Petersen et al., 2013); sensitivity auditing (Saltelli, Pereira, van der Sluijs, & Funtowicz, 2013); and the NUSAP notational system (van der Sluijs, 2017).

5.3.1 The Guidance approach of the Netherlands Environmental Assessment Agency

An example of a state-of-the-art approach to uncertainty assessment and communication at the science-policy interface is the *Guidance for Uncertainty Assessment and Communication* approach to knowledge quality assessment (the Guidance) of the Netherlands Environmental Assessment Agency (Haque et al., 2017; P. H. M. Janssen, Petersen, van der Sluijs, Risbey, & Ravetz, 2005; A. C. Petersen et al., 2013; van der Sluijs et al., 2008). The Guidance is a comprehensive framework that covers both the substantial and the societal dimensions of uncertainty and quality. It is a proven tool that has been in use for 15 years. The Guidance was developed in 2002 through a partnership between the Netherlands Environmental Assessment Agency and Utrecht University, and has become widely used in that agency. It has reportedly stimulated co-learning processes among scientific advisers and policymakers for a deeper understanding and awareness of uncertainty and its policy implications (A. C. Petersen et al., 2011).

The Guidance tool adopts a checklist approach, designed to transparently highlight and communicate uncertainties along a scientific assessment process as a way of structuring informed public and policy debate, whether for an Environmental Impact Assessment for a particular project, or for a broader assessment of the body of knowledge used to inform a policy programme (e.g. P. H. M. Janssen et al., 2005; A. C. Petersen et al., 2013; van der Sluijs et al., 2008). It does not limit its focus to formal, quantitative methods for sensitivity and uncertainty analysis, but extends its scope to the social context of knowledge production, including assumptions and value-loadings. In this way, it systematically guides scientists in an exploration of deeper uncertainties that reside, for instance, in problem framings, expert judgements, and assumed model structures. It provides a heuristic that encourages self-evaluative systematic critical reflection in order to become aware of pitfalls in knowledge production and use. It also provides diagnostic help as to where uncertainty may occur and why (van der Sluijs et al., 2008). The Guidance focuses on six elements of knowledge production and use (Table 3).

Phase in the assessment	Key uncertainty and quality issues to critically reflect upon
Problem framing	(i) Existing frames of the problem, other than that of end users; (ii) the interconnections with other problems; (iii) any other relevant aspects of the problem not addressed in the research questions; (iv) the role of the study in the policy process; and (v) the way in which the study connects to previous studies on the subject
Stakeholder involvement	(i) The relevant stakeholders; (ii) their views, roles, stakes and involvement with respect to the problem; and (iii) the aspects of the problem on which they disagree
Indicator/visualisation selection	(i) Adequate backing for selection; (ii) alternative indicators; and (iii) support for selection in science, society, and politics
Appraisal of knowledge base	(i) The quality that is required; (ii) the current state of knowledge; and (iii) the gap between these two
Mapping and assessing relevant uncertainties	(i) The relative importance of statistical uncertainty, scenario uncertainty and recognised ignorance with respect to the problem at hand; (ii) the uncertainty sources that are most relevant to the problem; and (iii) the consequences of these uncertainties for the conclusions of the study
Communication of uncertainty information	(i) Context of reporting; (ii) robustness and clarity of main messages; (iii) policy implications of uncertainty; (iv) balanced and consistent representation in progressive disclosure of uncertainty information; and (v) traceability and adequate backing

Table 3. Criteria and key issues for knowledge quality in the Guidance (A. C. Petersen et al., 2013).

5.3.2 Sensitivity auditing

Another checklist-based tool that helps to make sense of and gauge the reliability, relevance and legitimacy of model-based inferences is sensitivity auditing (Saltelli & Funtowicz, 2014; Saltelli et al., 2013). Applying sensitivity auditing implies running through a checklist:

- Rule 1: 'Check against rhetorical use of mathematical modelling': are results being over-interpreted? Is the model being used ritually or rhetorically?
- Rule 2: 'Adopt an 'assumption hunting' attitude': this would focus on unearthing possibly implicit assumptions.
- Rule 3: 'Detect pseudo-science': this asks whether uncertainty has been downplayed, as discussed above, in order to present results in a more favourable light. This rule can be referred to as GIGO, from 'garbage in — garbage out', or as 'detect pseudo-science' (Funtowicz & Ravetz, 1990).
- Rule 4: 'Find sensitive assumptions before these find you': this is a reminder that the analysis of sensitivity should be done and made accessible to researchers before publishing results.
- Rule 5: 'Aim for transparency': this rule echoes present debates on open data and of the need for a third party to be able to replicate a given analysis; see e.g. the Peer Reviewers' Openness Initiative (Morey et al., 2016), intended to

discipline authors into providing complete access to the materials used in the preparation of articles, or the San Francisco declaration (American Society for Cell Biology, 2012), as well as Ioannidis's paper on *How to Make More Published Research True* (2014).

- Rule 6: 'Do the right sums': the analysis should not solve the wrong problem — doing the right sums is more important than doing the sums right. This points to quantitative storytelling, discussed below. In summary, this rule is about asking whether the given quantification is not neglecting important alternatives ways to frame a given example.
- Rule 7: 'Focus the analysis on the key question answered by the model, exploring holistically the entire space of the assumptions': this rule is a reminder of good sensitivity analysis practice to run sensitivity analysis globally. Additionally, the object of the analysis should not be the model *per se*, but the inference of policy being supported by the model. Fragility and volatility are, in fact, not attributes of the model as such, but of the model as used to answer a particular question. An important implication of this rule is that a model cannot be audited for sensitivity once and for all, but needs to be re-audited in the context of each specific application of the model.

This checklist may be seen to pose a burden on the analyst; however, when a scientific analysis is intended to inform an important policy process, it is reasonable to ask that methodological standards be set high (Funtowicz & Ravetz, 1990).

5.3.3 NUSAP

The NUSAP system for uncertainty assessment (Funtowicz & Ravetz, 1990; Refsgaard et al., 2007; van der Sluijs, 2017; van der Sluijs et al., 2005) aims to provide an analysis and diagnosis of uncertainty in science for policy. The basic idea is to qualify quantities by using the five qualifiers of the NUSAP acronym: numeral, unit, spread, assessment, and pedigree.

NUSAP complements quantitative analysis (numeral, unit, spread) with expert judgement of reliability (assessment) and systematic multi-criteria evaluation of the different phases of production of a given knowledge base (pedigree). Pedigree criteria can be proxy representation, empirical basis, methodological rigour, theoretical understanding and degree of validation. Pedigree assessment can be further extended to also address societal dimensions of uncertainty, using criteria that address different types of value ladenness, quality of problem frames, etc.

NUSAP provides insight on two independent uncertainty-related properties expressed in numbers, namely spread and strength. Spread expresses inexactness whereas strength expresses the methodological and epistemological limitations of the underlying knowledge base. The two metrics can be combined in a diagnostic diagram, mapping strength of, for instance, model parameters and sensitivity of model outcome to spread in these model parameters. Neither spread alone nor strength alone is a sufficient measure for quality. Robustness of model output to parameter strength could be good even if parameter strength is low, if the spread in that parameter has a negligible effect on model outputs. In this situation, our ignorance of the true value of the parameter has no immediate consequences. Alternatively, model outputs can be robust against parameter spread even if its relative contribution to the total spread in the model is high, provided that parameter strength is also high. In the latter case, the uncertainty in the model outcome adequately reflects the inherent irreducible (stochastic) uncertainty in the system represented by the model. Uncertainty then is a property of the modelled system and does not stem from imperfect knowledge on that system. Mapping components of the knowledge base in a diagnostic diagram thus reveals the weakest spots and helps in setting priorities for improvement (Boone et al., 2009; Pye et al., 2018; van der Sluijs et al., 2005).

The strength of NUSAP is its integration of quantitative and qualitative uncertainty. It can be used on different levels of comprehensiveness: from a 'back of the envelope' sketch, based on self-elicitation to a comprehensive and sophisticated procedure involving structured, informed, in-depth group discussions on a parameter-by-parameter format. A limitation is that the scoring of pedigree criteria is based on expert judgements. Therefore, outcomes may be sensitive to the selection of experts. It is thus advisable to involve a diverse group of experts in the pedigree scoring (van der Sluijs, 2017).

5.4 GUIDELINES FOR TAKING POTENTIAL SOCIAL IMPACT INTO ACCOUNT

Any scientific advisory process or system is well advised to involve not only scientists and policymakers but also a wide range of social scientists and, in addition, societal actors (see Section 5.5), to take into account the potential social impact of the advice (Organisation for Economic Co-operation and Development, 2015). For natural scientists, it is a challenge to translate research results and conclusions into advice that would be useful for policymakers and, at the same time, take possible social impacts into account (Organisation for Economic Co-operation and Development, 2015). One of the main difficulties is that scientific evidence is almost always accompanied by uncertainty, which leads to different opinions among scientists. This requires them to provide their advice and expertise with degrees of probability, which is not easily accepted by policymakers. Often, it is considered to be a lack of reliable knowledge and the tendency to ask (too) many different groups of experts for opinions. Diverse opinions of scientists are the natural consequence of scientific methodology and this is not a shortcoming (Organisation for Economic Co-operation and Development, 2015). For example, data collection depends on how a question is formulated. It is advisable to try to reach a consensus, first within the scientific community (the national scientific councils), and later in communicating with society and policymakers.

In a situation when differences in scientific opinions remain, the reasons and underlying assumptions should be clearly identified and communicated, addressing the limits of science and the essence of uncertainty in scientific research (Kloprogge, van der Sluijs, & Wardekker, 2007). Managing uncertainties is difficult but critical for scientific opinion (see Sections 5.1 and 5.2). Doubts about empirical data (evidence versus experience) or statistical uncertainty may be expressed in terms of probabilities in those cases where some form of uncertainty quantification is justified; otherwise, qualitative accounts of uncertainty or combinations of qualitative and quantitative uncertainty information will also be appropriate (Risbey & Kandlikar, 2007; van der Sluijs et al., 2005; van der Sluijs et al., 2008; Wardekker, van der Sluijs, Janssen, Kloprogge, & Petersen, 2008). For that reason, some examples of scientific advice have been contested as not conclusive enough (Organisation for Economic Co-operation and Development, 2015).

Scientific advisers need to explain what aspects of the knowledge are uncertain or contested and why, and present this information in a comprehensible way to policymakers (Organisation for Economic Co-operation and Development, 2015). Politicians are used to dealing with uncertainty (when considering, for example, polling information), but when it comes to scientific opinions they often expect that science can provide unambiguous answers and are insufficiently aware of the limits of science (Organisation for Economic Co-operation and Development, 2015). Therefore, instead of making comments about policymakers not understanding uncertainty, it is better to explain what knowledge and skills would help policymakers to deal with uncertain information (Sutherland, Spiegelhalter, & Burgman, 2013). In Section 4.4, some strategies to communicate uncertainty to policymakers have been described which should be used in conveying uncertainty to policymaking bodies. At the same time, scientists need to ensure that their expertise/opinion/advice meets the highest quality standards. As a general rule, a peer review process is required in order to include experts from a wide range of disciplines, including social sciences, humanities and design/communication experts (Organisation for Economic Co-operation and Development, 2015).

It seems that a major factor which determines the importance or impact of research-based advice is transparency in communicating to policymakers as a means to avoid misunderstanding. There are two ways to reach a final version of an opinion. Often, advisory bodies follow a custom (a rule) not to communicate before the opinion is known to the public and, in the case of differences among experts, minority views are included in the final version (Organisation for Economic Co-operation and Development, 2015). In this case, experts are free to communicate eventual disagreement over the final version of the report. In the other cases, early communication of a draft opinion might be necessary. This, however, requires special attention paid to transparency, and any advice based on preliminary or incomplete results needs an acknowledgement that any later change in the interpretation of research data and additional collection of evidence are clearly marked as such, otherwise it could lead to mistrust in an advisory body (Organisation for Economic Co-operation and Development, 2015). In general, it is advisable to provide scientific advice to both the public and decision-makers simultaneously (Organisation for Economic Co-operation and Development, 2015).

As an example, the report of the Global Science Forum (Organisation for Economic Co-operation and Development, 2015) gives the procedure of the Intergovernmental Panel on Climate Change as a model (Intergovernmental Panel on Climate Change, 1998/2013):

> ***'The Panel prepares a draft of the report, including all findings of the different expert groups. After the first order draft has been reviewed, authors prepare a second order draft and a first order draft of its Summary for Policymakers. The second order draft of the report and the first draft of the Summary are subject to simultaneous review by governments and experts. Authors then prepare final drafts of the report and Summary. These are distributed to governments who provide written comments on the drafts before meeting in plenary to approve the Summary and accept the report. This dual process has been adopted by a number of scientific advisory bodies at both international and national level'***
>
> (Organisation for Economic Co-operation and Development, 2015).

The dual report process may help to improve in the communication of scientific advice, including the appropriate formulation and language. It is a challenge to write the report for policymakers and as an open access publication, on the one hand, that satisfies the scientific audience by using scientifically accurate and precise language, and on the other hand, that reaches a more general audience by using an easy-to-understand common language (Organisation for Economic Co-operation and Development, 2015). The term 'appropriate language' is used in the process of achieving such an improvement in scientific reports (Organisation for Economic Co-operation and Development, 2015). In conclusion, when translating evidence and research findings as part of a policy-relevant expertise process, the importance of transparency, openness and stating uncertainties in scientific conclusions cannot be emphasised enough.

Beyond the domain of environmental and health-related advice, scientific advisory bodies address many important policy issues such as education, security, infrastructure or defence. A major issue in assessing impacts in these domains is the degree to which scientific evidence is available, or can be produced in due time. However, many policy domains require less empirical information about impacts, but rather expertise in the form of prudent judgement or holistic enlightenment. Experts are asked to consult with policymakers about potential solutions rather than providing numerical assessments of likely impacts (Wadhwa, Barnard-Wills, & Wright, 2015). Furthermore, impacts may vary, depending on the perspective and experience of the groups that are affected by policies, including end-users, stakeholders, researchers, policymakers and NGOs (ASSERT — Assessing Security Research: Tools and Methodologies to Measure Social Impact, 2013).

5.5 GUIDELINES FOR INTEGRATING DIFFERENT TYPES OF KNOWLEDGE INTO THE POLICY PROCESS

As the EU white paper on governance noted:

> *'Knowledge used for policy-making and public debate should not only be excellent from a scientific point of view; it also needs to be 'socially robust', responding to policy, social, economic needs or concerns. This involves expertise beyond traditional and professional 'peer' community to include those with practical or other knowledge about the issue at hand.'*
>
> (Liberatore, 2001).

In Section 3.4, we discussed the plurality of relevant knowledge beyond scientific information and evidence. It is now widely acknowledged that in democratic decision-making, relevant wisdom is not limited to scientific specialists and public officials (Kloprogge & van der Sluijs, 2006; P. C. Stern & Fineberg, 1996). The political decision-maker should thus not only consider the technological and scientific data, specifying as clearly as possible what is known, what is uncertain and what is unknown. In addition, a plurality of perspectives from across diverse knowledge systems, such as traditional knowledge, craft skills and know-how, institutional knowledge and tacit knowledge should be mobilised through dialogue and included where relevant (Bremer, 2013; Renn, 2010). (See also Section 3.4).

Local knowledge can include knowledge of local conditions, which may determine which data are strong and relevant. It can also be anecdotal or it can be official information published by unofficial means (through, for example, whistleblowing or investigative journalism) (Funtowicz & Ravetz, 1996). Warren (1992) described local or indigenous knowledge as knowledge that is unique to a given culture or society. It often contrasts with the scientific knowledge system generated by universities, research institutions and private firms. It is the basis for local-level — decision-making in agriculture, health care, food preparation, education, natural-resource management and a host of other activities in rural communities (Warren, 1992). Indigenous knowledge is used synonymously with 'traditional' and 'local' knowledge to differentiate the knowledge developed by a community from the global knowledge systems generated through universities, government research centres and private industry. Indigenous knowledge refers to the knowledge of indigenous peoples, as well as any other defined community (Warren, 1992).

This societal aspect of science advice implies that it is not based on individual expertise but on collective expertise, often involving experts and expertise also from outside of academia. However, the opinions of experts often diverge. Collective expertise therefore has to deal with the problem of conflicting and minority opinions in order to be trustworthy and useful (European Food Safety Authority, 2006; Science Advice for Policy by European Academies, 2017). A prior outreach presentation is needed to convey the different facets of the problem to a politician who does not have the appropriate background. This presentation must make it clear that different opinions are possible and why they have emerged (see also Organisation for Economic Co-operation and Development, 2015).

In this respect, two strategies could be useful. The first is to involve two types of participants: experts with different, even opposite views, and 'devil's advocates' whose role is to challenge the experts, to reveal contradictions and to distinguish between opinions relating to a conflict of emotional or financial interest from opinions based on facts. The challenge is to present these controversies in a form usable by a political decision-maker (Martin & Richards, 1995).

The second strategy is to use a grid of analysis called 'ethical questioning' that helps to address all a new process or technology's impacts on the different facets of human life, both positive and risky, of a new process or technology (e.g. Kaiser, Millar, Thorstensen, & Tomkins, 2007; Stilgoe et al., 2013). The reference values are, on the one hand, the concepts of freedom, equality and solidarity and, on the other hand, the Universal Declaration of Human Rights (United Nations General Assembly, 1948).

The credibility of the experts is crucial. The declaration of conflicts of interest of the individual is necessary but insufficient (E. A. Boyd & Bero, 2006). It seems important to take into account also emotional or ideological conflicts of interest. It may be difficult for experts not to have a very positive bias for a technology they have been developing in the hope of contributing to a better life for humanity. The fact that an expert cannot be completely objective underlines the need of the contribution of 'devil's advocates' in the construction of science advice for decision-makers (e.g. Schwenk & Cosier, 1980).

The credibility of science advice is not related solely to its scientific merits but also to the ethical and societal acceptability of the technology in question by the general public, citizens and society at large (Cash et al., 2003). O'Connor (1999) distinguishes two notions of 'integrating knowledge' for governance, based on contrasting notions of reconciliation: Cartesian vs dialogical.

The Cartesian perspective of integration is based on Laplacian reconciliation: all knowledge is integrated within an internally-consistent conceptual framework; Cartesian epistemology privileges 'objective' description and explanation based on axiomatic categories for system description. This notion of integration is characterised by a domination ethic: knowledge is used instrumentally to govern a cause-effect relationship; calculation, prediction and contractual certainty are privileged (O'Connor, 1999).

Alternatively, the dialogical perspective acknowledges the plurality of perspectives in co-existence and collective understanding. It accepts that the multiple perspectives in society are often irreducible to one single vision, or immeasurable according to one measure of validity, and allows them to exist side-by-side. Integration is then based on dialogical reconciliation of the diversity of perspectives and modes of understanding in an irreducible plurality. The corresponding complexity epistemology fosters an irreducible plurality of pertinent analytical perspectives. This notion of integration is characterised by a hospitality ethic: knowledge pursued and exploited based on norms of courtesy and dialogue; tolerance of tensions, and admission of antagonisms (O'Connor, 1999).

Depending on the function of scientific advice to policymaking (see Section 4.2), the instrumental version of science advice is more adequate if policymakers search for strategies to reach a pre-defined goal, while the dialogical perspective is more adequate if the goal of advice is to co-create new knowledge or to provide better orientation to policymakers (Bremer, 2013). The enlightenment function may be served by both perspectives, depending on the issue in question.

As Bremer (2013) has argued, amongst others, wicked problems (see Sections 2.1 and 5.2) best fit with the dialogical perspective on integration. Many policy issues and problems seem to fit the description of wicked problems and require input from a plurality of sources and types of knowledge (see also Section 3.4). This fits well with the function of co-creation or co-generation (Mauser et al., 2013). It involves three fundamental steps throughout which both scientists and stakeholders are involved to varying degrees: co-design, co-production and co-dissemination (Mauser et al., 2013). During these consecutive steps, three dimensions of integration (scientific, international and sectoral) are of varying importance to the overall knowledge creation process.

In the field of technology assessment, similar insights have emerged. The impact of technologies on different aspects of human life must be made clear, and the appropriate use of the Precautionary Principle must be taken in account (Von Schomberg, 2012). The decision-maker must understand the values involved in order to be able to act in full awareness and knowledge (Lucivero, Swierstra, & Boenink, 2011). Such impacts of the decisions to be taken on the different aspects of human life, directly or through the environment, can be addressed by ethical questioning (Kaiser et al., 2007; Stilgoe et al., 2013). Possible impacts of new technologies and processes on human life can be identified as follows (e.g. Stilgoe et al., 2013):

- During the stages of design, construction and use, was the technology submitted to assessment of its risks and benefits?
- Does the development and diffusion of the technology modify the private sphere, and in what way; for instance inter-individual relations, the fundamental structures of social life or the environment?
- Does the development and diffusion of the technology modify, and in what way, the major areas of human activity, such as food, education, health, employment or the economy? Or social, cultural and political life, defence? Are there spiritual or philosophical aspects to be considered?
- What level is considered to be appropriate for controlling the appropriate use of the technology? The citizen, public or private organisations or state levels? Does it affect international relations?

The following sections include some major insights from studies that link process design factors with quality assurance of the advice.

5.6 GUIDELINES FOR INTEGRATING VALUES IN EVIDENCE-INFORMED DECISION-MAKING

In Section 3.5, we discussed the role of normative assumptions and values in scientific knowledge. Here, we review the available practices for integrating values in evidence-informed decision-making. The set of values that a scientific community brings into play, as well as our interests, would play a major role in deciding which of the decision options are acceptable and how much risk is tolerable, given a specific expectation for benefits (Douglas, 2009). Furthermore, how risks and benefits are distributed among different populations, groups or individuals, gives rise to issues of social justice and fairness. Hence, ethical values play a pivotal role in examining the consequences of error for the general public (Douglas, 2009).

In particular, ethical values help scientists and policymakers alike to weigh whether potential benefits are worth potential harms, whether some harms are worth no price, and whether some harms are more egregious than others (Douglas, 2009). Examples of ethical values relevant to scientific research include the rights of human beings not to be used for experimentation without fully informed consent; the consideration of sentient beings for their pain; concern for the death and suffering of others; whether it is right to pursue research for new weapons of mass destruction; and whether an imposition of risk is ethically acceptable (Douglas, 2009). Scientists, Douglas claims, have an ethical responsibility to consider the possible consequences of their errors, in particular in instances where their theories are used as guidelines for policy decisions.

The plurality of knowledge claims and criteria of justification, and the justificatory gap between science and other forms of knowledge also highlight the role of value judgements in choosing between alternative sources of knowledge and justificatory schemes (Hisschemöller et al., 2001). Faced with conditions of uncertainty, together with the possibility of risks, it is not surprising that those at the receiving end of scientific advice will be more inclined to put their trust in what is familiar and well-tested, i.e. the claims of common sense and deeply-held intuitions, rather than opting for claims to knowledge that are not yet fully established (see Section 3.4). It is important to note that such decisions of withdrawal of trust are based on fully legitimate expressions of personal and familial interests and should not be dismissed as indicators of a deficit in knowledge or information (Wynne, 1992a). Science that addresses wicked problems requires more reassurance, and the reassurance will and should involve value judgements about the risks of error on the part of the scientific advisers (Wynne, 1992a).

Even if one accepts the idealistic notion of a value-free science, in the manner advocated by Lacey (1999) and many others, the question of which values should be prioritised in considering scientific evidence remains unanswered. The problem is particularly acute if one bears in mind that values, no less than standards of justification, are informed by local customs and traditions and may vary and even come into conflict (Douglas, 2009). A bridge between the procedures and methods of reasoning used in science and the social and moral values implicitly invoked by science can be established by looking at the type of epistemic norms employed by scientists and their connections with the norms and values in the moral and social domains (e.g. Douglas, 2009).

Good science is science that is performed with integrity, honesty, care for accuracy, and intellectual humility — the state that comes with the acceptance of the provisional nature of all scientific findings and the fallibility of the individual scientist (Kaiser, 2014). It is important to note that these intellectual or epistemic virtues necessary for good science are also ethical virtues. To show integrity in the lab is to be a person of integrity. To be open and honest in writing the results of an experiment is to be an honest person. To be alert to your own errors is to put aside arrogance as a character trait. Thus, the values and virtues necessary for conducting good science are not distinct from some of the ethical virtues and values we employ in broader social contexts.

A consensual way of defining the values that arrangements for science advice for policymaking must respect is to refer to the Universal Declaration of Human Rights, which focuses on the recognition of the dignity of the human person regardless of age, social origin, culture or religion (World Commission on the Ethics of Scientific Knowledge and Technology, 2005). This recognition of the dignity of human beings restricts the instrumentalisation of humans and gives human rights a priority over power and profit. The recognition of human rights can be detailed according to three prime ethical values: freedom, equality, solidarity.

- Freedom of thought, religion, expression; freedom to undertake, to travel; respect for personal, private, material and psychological territory, from which this freedom can be expressed.
- Equality, in the form of diversity of gifts, tastes and sensibilities, must be respected in every human being who must have the same value, dignity, access to education and health, and access to a fulfilling work associated with a remuneration allowing a dignified life and leisure.
- Solidarity, also around societal projects. The construction of a social body, for example, is at the heart of the ethical issues of communication technologies. They can be used, or not, to promote solidarity and the awareness of a common destiny at all levels of social life.

More specifically, the European Group on Ethics in Science and New Technologies (2018) highlighted the following ethical principles as recommended benchmarks for informing science advice to policymaking: human dignity, autonomy, responsibility, justice (equity and solidarity), rule of law and accountability, security (safety, bodily and mental integrity), data protection and privacy and sustainability. The report provides explanations of how these principles can and should be implemented. In Section 5.7 we revisit some of these principles and relate them to science advisory bodies.

One aspect of conducting good science refers to the issue of unequal access to scientific advice, but also of unequal access of different knowledge communities to policymakers. This deficit in true representation of all relevant knowledge camps has been called *epistemic injustice* in the literature. Epistemic injustice refers to the idea that social power ensures that the knowledge of some groups is excluded from the collective epistemic resources and others are over-represented (Carel & Kidd, 2014; Fricker, 2007). This has been investigated, in particular, in the context of health-related knowledge. In the area of scientific advice to policymaking too, there is ample evidence that particular expertise is not included, or at least underrepresented in scientific advisory bodies (see cases in Kidd, Medina, & Pohlhaus, 2017). However, it is also not obvious which epistemic groups should be represented in an advisory body and who determines the composition of such bodies (Lentsch & Weingart, 2011b). The minimum requirement is transparency in how candidates were selected and what criteria were used to determine which expertise is needed. Furthermore, openness for epistemic communities that were not initially asked to be included in the advisory bodies may be another mechanism to avoid epistemic injustice (Pohlhaus, 2006).

Similarly, Goldman has addressed the issue of epistemic asymmetry (Goldman, 1999, 2001). This asymmetry refers to different access to define and use reliable knowledge, and to distinguish between reliable and non-reliable experts. Goldman refers to five criteria that can help to judge reliability of knowledge claims. Yet the resources to apply these criteria are not equally distributed among the targeted audiences. Furthermore, it is possible to select the experts and frame the expertise in a way that the evidence produced appears reliable although it would not pass the test for reliable and robust knowledge (McIntyre, 2018). Epistemic asymmetry underscores the need for defining values and virtues for both sides, that is, for scientific advisers and policymakers to arrange a setting in which all relevant evidence is represented and knowledge claims are fairly scrutinised.

Even if one can agree on values, it only modestly illuminates the ethical decision. The ethical consequences of a decision depend on the priority given to a value. The necessity, for a policy decision-maker, to choose between well-established values may result in ethical conflicts.

Examples of ethical conflicts include:

- How to strike a balance between innovation that accepts risks, and the Precautionary Principle that wants to eliminate them? (Innovation versus safety).
- How to justify complexification of pharmaceutical regulation making the development of cheap drugs impossible and the increasing cost of the therapeutic progress excluding most of the world from these progresses? (Efficacy/safety versus availability).
- How to integrate the development of robotics with the change of work life that robotics causes? (Less arduous and more high-skilled work versus work for everyone).

- Will precision medicine lead to more individualised services or to an instrumentalisation of the human being? (Control of the living versus respect for the living).
- How should societies regulate and control data collection, processing and interpretation given the fact that the collection and analysis of very large volumes of data (Big Data) makes it possible to obtain extremely precise information on individuals and to offer powerful personalised services in the field of health, security, finance and other areas of social life? (Tailored services versus respect for privacy).

The ethical reflection on the arrangements for the science-policy interface is therefore constantly confronted, with a dynamic balance between individually perfectly respectable values but resulting in very different choices depending on the priority given to one or the other. The ethical approach is constantly advancing between opposing values. Science advisers and policymakers need to address these issues and to be aware of this dynamic balance in order to avoid potential 'shipwrecks'. The Universal Declaration of Human Rights proposes to give priority to values centred on the human and therefore acceptable to all, whatever their cultures, religions or individual sensitivities. The key to ethical choices in selecting and prioritising policy options is to give priority to humans in their environment and not to the otherwise legitimate power or profit.

Scientific data, information and knowledge need to be summarised in a concise and understandable form, with clear conclusions including pertinent ethical and societal considerations. A summary underlining the lessons learned could be useful but the recommendations are usually the responsibility of the mediators. It must be stressed that the politician makes evidence-informed decisions, not evidence-based decisions, because the decision will be influenced by his/her political values as well as economic constraints and social acceptability.

Synthesising best practices from the literature, the following section will outline the design principles for a high-quality transdiciplinary approach to the use of scientific and other relevant knowledge at the nexus between science and policymaking.

5.7 BUILDING A TRANSDISCIPLINARY APPROACH FOR DESIGNING A WORKING INTERFACE BETWEEN EXPERTISE AND POLICIES

5.7.1 Emerging design principles for the 'working interface'

In Section 3.6, the process of science advice to policy was discussed, focusing on mechanisms of quality control, questions of the efficacy of scientific advice/information and the norms and expectations at intersections of science, policy, and practice. In this section, the focus is on the design principles for a working interface that takes account of the state-of-the-art insights and practices for a high quality, transdisciplinary interface between knowledge and policymaking.

In order for any aspect of any policy process to be consistently recognisable as being positive under diverse political views, it is desirable that there be clarity concerning explicit criteria for what constitutes 'good conduct' (European Commission, 2004; Rogers, 2008). Although such criteria are inevitably always to some degree uncertain, ambiguous, dynamic and context- and perspective-dependent (and therefore always negotiable), they nonetheless offer a basis for continual evaluation, improvement and redesign of 'best practice' (Wilsdon et al., 2014). Respected as 'design principles' which apply also to their own continuous re-negotiation and application, then, such criteria can aid policy actors of all kinds in engaging with each more effectively, efficiently and productively (S. Beck et al., 2014; Fischer, 2009; Stirling, 1999). It is not the purpose of this report to advocate particular extant evaluative criteria as normative principles. Yet there is much that can usefully be done analytically to illuminate the kinds of issues that are most prevalent in relevant literatures bearing on the working interface between expertise and policy.

Based on wide and longstanding literatures concerning good practice in the field of policy advice from and for science (e.g. European Commission, 2015; Fealing, 2011; Frickel & Moore, 2006; Gibbons et al., 1994; International Network for Government Science Advice, 2017; Keller, 2009; Lentsch & Weingart, 2011b; Pielke, 2007; Pielke & Klein, 2010; Sarewitz, 2015; Sorlin, 2015; Sutherland et al., 2012) , the following broad issues come to the fore. They are characterised here in analytic and descriptive terms, rather than as normative prescriptions. The criteria most directly bearing on the task of characterising, partitioning and ordering relevant issues are the following:

- Each is broadly relevant in individual terms to the present focus on the task of '*building a transdisciplinary approach for designing a working interface between expertise and policies*';
- Each is particularly prominent and well-developed in existing policy debates as well as distinct and readily operational in practice;
- The set of resolved issues is, despite areas of overlap, tension or ambiguity, collectively coherent as a group.

Accordingly, the issues summarised here are, in rough order of flows in policy cycles, about 'trustworthiness': 'independence'; 'transparency'; 'inclusiveness'; 'accessibility'; 'responsiveness'; 'deliberation'; 'rigour'; 'precaution'; 'responsibility' and 'democracy'.

5.7.2 Trustworthiness

One significant positive quality, repeatedly referred to on all sides of political debates concerning policy advice from and about science, involves various notions of 'trust' (Herreros, 2004; R. Löfstedt, 2005; Porter, 1995; Siegrist, Earle, & Gutscher, 2010; Slovic, 1999). At one level, the quality of trust is a self-evident public good, which (at its best) helps enable good practice, robust institutions, healthy discourse and effective social outcomes (Brewer & Ley, 2013; Büscher & Sumpf, 2015). Yet there also arise a number of queries concerning many established ways of thinking about trust. First, it is important to note that relations of trust are only clearly positive under all views, if they are mutual, reciprocal and symmetric as between different actors involved in policy processes (Economic and Social Research Council Global Environmental Change Programme, 1999). In particular, trust should be demonstrated as much 'downwards', by actors in positions of privilege and power (towards other interested and affected parties and publics), as 'upwards' to the benefit of incumbent interests and cultures in any given policy process (Haerlin & Parr, 1999). Otherwise, the language of 'trust' can become an instrumental code in support of inequalities, patronage and dependencies of kinds that favour incumbency and privilege and (at worst) risk becoming a smokescreen merely for 'public acceptance' (Flynn & Bellaby, 2007; Stirling, 2008; Wynne, 1983).

Second, it also emerges strongly, that trust is only a self-evident positive quality if it is grounded in substantive practice rather than rhetoric (Wynne, 1975). This means in relation to all social actors engaged in policy processes around expert advice for and from science, that the legitimate exercise of diverse values, interests and understandings should be undertaken in ways that are not merely 'trusted' in superficial communicative terms, but 'trustworthy' in their underlying material practice (Hardin, 2002; Kornai & Rose-Ackerman, 2004; Korsgaard, Brodt, & Whitener, 2002). This can be enhanced if representatives of the affected stakeholder groups are included in the governance process and have full access to the scientific advice (Kim & Lee, 2012; Webster & Leleux, 2018).

5.7.3 Independence

Arguably, one of the most prominent issues raised in policy literatures bearing on expertise in governance concerns 'independence'. It is in the nature of policy processes around expert advice — as well as decisions concerning science itself — that these necessarily involve not only complex bodies of knowledge, but also contending social values and interests (Felt et al., 2007). Even where all concerned act in good faith, the policy arenas around such processes are routinely characterised by high political and economic stakes and asymmetric gradients of power (Stirling & Mitchell, 2018). In addition, the expert knowledge itself is typically partly shaped and mediated by the particular institutional cultures in which it is developed, involving specific framings of 'salient problems' and 'possible solutions' as well as more general areas of focus and emphasis (sometimes necessarily sidelining various other aspects) (Jasanoff, 2005b). Occasional tensions and contestations can also often arise not only at the levels of individual experts, committees and agencies (Taig, 2002), but also between disparate academic organisations, disciplines and cultures (Jasanoff, 2011a). It is in the nature of science itself that such tensions can — if they are openly acknowledged and transparently managed — make contributions to the robustness and productivity of the resulting combined understandings (Grayling, 2008). Yet it is when these asymmetries and dynamics of power, privilege and contending values and interests within science are obscured or denied that policymaking can be placed at greatest risk of being considered in some way 'untrustworthy' (Alan Irwin & Wynne, 1996).

To this end, respect for the importance of 'independence' is not about making claims to ostensibly transcendent objectivity and definitiveness on the part of notionally singular and self-confident 'sound scientific' prescriptions (Gorman, 2002). What is entailed and required instead in much discussion of 'independence' is open recognition that values and interests are always unavoidably intrinsic to any body of scientific expertise (Sarewitz, 2004). This illuminates a distinction between alternative aspirations, that might be termed 'independence through transcendent authority' and 'independence through robust plurality' (Voss, Bauknecht, & Kemp, 2006). The former asserts traditional romanticised notions of scientific expertise (themselves ironically oddly unscientific in the ways they assert authority over process) (Lacey, 1999). In the latter case, aiming for independence is always provisional, lying in explicit acknowledgement of the different ways in which contrasting forms and conditions of expertise typically give rise to divergent pictures of problems and solutions (Collins & Evans, 2007). Here, it is arguably by means of methods that systematically show how contrasting conclusions can arise under alternative framings in 'plural and conditional' ways that science advice processes may most confidently be considered 'independent' (Stirling, 2010).

5.7.4 Transparency

In wider debates concerning criteria of good practice in governance of the most general kinds, one of the most widely discussed issues is transparency (R. W. Oliver, 2004). That the evidence base and processes of reasoning behind any given area of policymaking be open to public scrutiny and validation is of obvious benefit in helping to ensure the robustness of the resulting decisions. However, even in these terms, transparency is not an unqualified public good (O'Neill, 2002). The issues surrounding this quality are not self-evident (Neyland & Woolgar, 2002). For instance, efforts at transparency can often come at significant cost (Aven & Renn, 2010) and it is important that these costs on the part of particular actors are justified by benefits on a wider societal basis (Gupta, 2008). Where transparency entails the production of bewildering volumes of discussion or data (without due attention to organisation, prioritisation or explication), then (something that might be misconstrued as) transparency can even become an obstacle to effective policy processes (Lord, 2006).

Likewise, if efforts at transparency have the real-world effect of pushing those actors who are thereby exposed to political jeopardy, into more informal and less well-documented avenues for decision-making, then measures intended or labelled as 'transparency' can also be counter-productive (Henriques, 2007). It is sometimes the case that provision of specific informal and private spaces for mutual awareness-raising can offer important complements to wider disciplines of transparency (Andersson, 2008). Taken together, it is regarded across a wide range of literatures to be an important aid both to effective decision-making and the associated demonstration of trustworthiness in policymaking on and by science, that it be possible for third parties to interrogate the basis for associated understandings and modes of reasoning.

5.7.5 Inclusiveness, accessibility and responsiveness

A wide variety of vocabularies are routinely used in policymaking by and for science, in order to refer to general distinct but inter-related qualities that might be referred to as 'inclusiveness', 'accessibility' and 'responsiveness'. Debates over related issues are often organised around discussions of terms like 'social inclusion', 'stakeholder engagement', 'public participation', 'community involvement', 'two-way dialogue', 'citizen science' and 'citizen efficacy' (Heinelt, 2002; Alan Irwin, 1995; Parliamentary Office of Science and Technology, 2001; Simonsen & Robertson, 2013; Stilgoe et al., 2009). At root, all these discussions are about various aspects of the societal 'fairness' (as distinct from expert 'competence') of policy processes (Renn, Webler, & Wiedemann, 1995). Across a diversity of debates, a host of wider detailed considerations and criteria variously come to the fore under this rubric. As this debate has developed, attention has turned from individual exercises towards mapping wider 'ecologies of participation' (Chilvers, Pallett, & Hargreaves, 2018). There arise not only many important detailed insights into good practice, but also many areas of ambiguity and axes for trade-offs and contestation (Chilvers & Kearnes, 2016; Alan Irwin, Jensen, & Jones, 2013).

Participatory practices may, for instance, be advocated normatively, because they may be held in and of themselves to be 'the right thing to do' in a democracy (Fiorino, 1990). They may be supported more instrumentally, because such practices can be seen to offer more effective means to secure particular pre-meditated or private ends (Levidow, 1998). They may also be argued more substantively, to offer the kind of diversity of inputs and qualities of interrogation that help lead to more generally societally robust policy outcomes (Stirling, 2012). For present purposes, however, it is possible to summarise these wider debates — and an important body of established policymaking and commitments in the field of European policy advice by and for science —by reference to these three broad qualities.

Viewed in contrasting ways, discussions of 'inclusion' typically recognise that — all else being equal and insofar as possible — it is generally better that any policy for (or informed by) science be developed in ways that fairly include all those social actors who stand to be interested or affected (Nuffield Council on Bioethics, 2012; Organisation for Economic Co-operation and Development, 2003, 2005; Stilgoe et al., 2009; Stirling, 2006). Discussions of 'accessibility' typically recall that policymaking processes should not just make provision for the formally-invited inclusion of selected actors and interests that are held to be relevant under the particular view of those convening a policy process but should also be open to those who self-identify as being potentially interested or affected (P. C. Stern & Fineberg, 1996; van den Hoven, Doorn, Swierstra, Koops, & Romijn, 2014; World Health Organization, 2006). Attention to 'responsiveness' tends crucially to enjoin that respect for inclusion and accessibility in the above senses, is not just about communicative performance in the delivery of policy, but also about the substantive design of the directions for policymaking (Owen, Macnaghten, & Stilgoe, 2012). In these terms, the issues raised in these literatures are not just about 'how to do it?', but also about 'what to do?' (Stirling, 2001).

5.7.6 Deliberation

Issues of inclusion, accessibility and responsiveness can all be seen to focus most on the depth and diversity with which contending societal interests and perspectives are engaged with in policymaking on — or informed by — science. As such, they might be seen to be most focused on the political and institutional conditions associated with these policy processes and their relationships with outside interests. Also crucially important, however, are the qualities displayed within these processes of discursive interchange and collective reasoning. Again, there exist vast literatures bearing on policy processes that discuss variously-understood criteria of 'deliberative quality' (Parkinson & Mansbridge, 2012), 'communicative rationality' (Renn, 2008), 'epistemic pluralism' (Bohman, 1996) or 'public reason' (Lövbrand, Pielke, & Beck, 2011). In one dimension of their meanings, questions around deliberation have a bearing on the particular ways in which policy processes are undertaken, reminding that it is not enough to declare adherence to progressive principles and simply assume the achievement of conditions of 'ideal speech' (Habermas, 2001). Instead, for effective 'public reason' around science and technology, it is widely argued that continuous deliberate efforts are required in order to balance different kinds of cultural entitlement, institutional privilege and power relations within (as well as around) associated policy advisory processes (Jasanoff, 2012).

If bias is to be avoided towards the most privileged interests within such policy processes, deliberation is about the importance of affording symmetrical degrees of attention, respect and support for the expression of contending understandings and arguments. Crucial here is to recall that expert disciplines themselves are constituted of social institutions and networks as well as substantive bodies of knowledge — and so also hold interests that might become over-privileged (Gibbons et al., 1994; Knorr, Krohn, & Whitley, 1981; Nowotny, Scott, & Gibbons, 2003; Stirling, 2006). Another dimension of deliberation is about not just the conduct of a policy advisory process, but about its design. This recognises that it is often the case, in efforts to balance bias and undue power and privilege, that the 'devil is in the detail'. Apparently highly specific features of the design of a process can lead to disproportionate impacts on the outcomes. It is in this sense that the quality of deliberation can apply not only to the substantive content of expert deliberations, but also to exactly what might be meant by 'inclusion', 'accessibility' and 'responsiveness' in the interface process of any given setting (Renn, 2008). Deliberation is also a way to avoid the dominance of heuristics and biases, as explained in Section 4.3.

5.7.7 Rigour

A particular source of quality related to deliberation is treated as being so imperative in many literatures — for instance on 'evidence-based policy' reviewed earlier — that it requires consideration as an issue in its own right. Well acknowledged in debates about the crucial roles for science in policy, this refers to the obvious importance of the scientific rigour with which evidence is addressed and analysis undertaken and reported (I. Boyd, 2013; Felt et al., 2007; National Research Council, 2012). Indeed, it is this consideration that underscores most strongly why scientific expertise is of such great value in the underpinning of policy processes — and why science of different kinds offers such ubiquitously necessary (if not sufficient) inputs to — decision-making (I. Boyd, 2013; National Research Council, 2012).

An obvious immediate issue that comes to the fore here is that the diversity of scientific disciplines typically relevant to any particular practical policy issue rarely upholds only a single framework for adjudicating the rigour of analysis (Saltelli et al., 2016). As an obvious general point, different disciplines address divergent objects of attention — such as physical materials, environmental systems, biological processes, social dynamics and psychological factors. Each field can involve contrasting principles of rigour — including those associated with various analytic or interpretive, qualitative or quantitative, or positivist or constructivist frameworks. With respect to each focus, some kinds of expertise tend to take more reductive approaches, others are more systemic — again, involving different (often complementary) principles of rigour. Likewise, across all these dimensions, some expert disciplines offer sophisticated ways to be rigorous about aggregation across contrasting contexts or perspectives, while others focus more on how to differentiate clearly between contrasting contexts or perspectives.

One of the most important aspects of rigour in many prominent current discussions over expertise in policymaking concerns the most robust ways to produce valid conclusions from large datasets using disciplines like systematic reviews (Higgins et al., 2011; Higgins & Green, 2008) and randomised control trials (Pearce & Raman, 2014; Solomon, Cavanaugh, & Draine, 2009). Another issue that comes with this concerns the interpreting of contrasting possible meanings around various alternative ways to frame whatever might be considered the salient dimensions categories, parameters and protocols under which such validity is constituted (Wynne, 2014).

It is precisely because of these contrasting ways to understand what might be meant by 'rigour' in science that interdisciplinarity is so important in policy advice by and for science (Frodeman, 2010). But it is also widely argued that prioritisation of contrasting frameworks of rigour between disciplines is not just a matter for the specific disciplines themselves, but also for other parties with a legitimate perspectives on the problems and potential solutions at hand. It is in this latter sense that transdisciplinarity, as discussed above, is widely argued to offer a crucial source of rigour in policymaking for and by science (Hirsch Hadorn et al., 2008).

5.7.8 Precaution

As has been discussed earlier in this report (Sections 3.7, 5.2 and 5.3), of the crucial dilemmas around scientific uncertainty are some of the most important issues on which it is imperative to be rigorous in policymaking by and for science (Ravetz, 2004). And it is here that may be found what is arguably the most well-established (but also most controversial), body of literature concerning the appropriate roles for science in policy: the Precautionary Principle (Renn et al., 2009). Although a subject of great breadth and complexity (and often confusion and sometimes misrepresentation)

(Marchant & Mossman, 2004), the importance of precaution to rigorous and deliberative policymaking is at its heart quite straightforward (Gee et al., 2013; Harremoës et al., 2001). At root, the problems to which precaution is a unique response are the pressures to exaggerate the conditions under which conventional risk assessment offers an applicable, rigorous or robust basis for policymaking (Randall, 2011; Sunstein, 2003). By reminding of the importance of attending not only to risk, but also to scientific uncertainty, precaution allows space for more rigorous deliberation over the grounds for assuming particular probability distributions, choosing or prioritising the parameters across which these are computed, or otherwise framing the contexts in which these are held to apply (Dreyer et al., 2008).

This simple quality of precaution is also arguably an issue of rigour. It can be crucial in the use of science in policy because there exist many pressures both in science itself as well as in wider politics that act to diminish the attention given to uncertainty (Stirling, 2017; Wynne, 1992b) . Perhaps most important are the well-explored (but sometimes somewhat neglected) political dynamics of justification (Boltanski & Thévenot, 2006; Collingridge, 1980; Genus & Stirling, 2018). As a means to foster public trust, secure acceptance, or manage blame, the political benefits of justification do not necessarily rest on the substantive content of the associated decisions always being right. Justification can be a valuable commodity for maintaining orderly policymaking, even if the content of what has been closed down turns out to be wrong (Collingridge, 1982). So it is not as a decision rule in its own right, but as a way to balance against these kinds of pressure (and resist undue reliance on overly simplistic methods that might actually be wrong), that application of a principle of precaution may arguably offer its greatest value (Stirling, 2017).

5.7.9 Responsibility

An important complement to discussions of precaution, especially in more recent years, is a parallel move towards notions of responsibility. Indeed, although they do not often explicitly include key features of precaution, notions and practices around responsibility in research and innovation have to some degree begin to supplant this in some settings (Owen, Bessant, & Heintz, 2013). In this discourse, there emerge additional sets of qualities for guiding decisions on the particular directions in which to prioritise scientific or technological advance in any particular sector (Macnaghten et al., 2014). Under the rubric of responsibility, large bodies of recent highly policy-relevant literature help operationalise criteria that might otherwise be neglected under the pressures and stresses of real-world decision-making, including (alongside other issues already discussed here) variously-discussed qualities like anticipation, reflexivity and care (Genus & Stirling, 2018).

'Anticipation' refers to the importance of looking ahead not only to possible benefits from particular technologies, but also to potentially adverse effects, some of the most salient of which may be indirect as well as unintended (Guston, 2008). Likewise, 'reflexivity' refers to the quality of being able to reflect on the ways in which understandings of the roles of science for and in policy, are conditioned by the contexts in which these emerge. This enjoins greater levels of humility and pluralism with regard to alternative perspectives, than might otherwise be found (Ziman, 2000). And qualities of care are also a key part of responsibility, in reminding that many of the most negative impacts of past technological decision-making have been due to exaggerations and romanticisations of capacities for control (Groves, 2011). A pervasive message across different literatures is that policymaking on science and technology can become more responsible by attending instead to the importance of caring for (rather than aiming or claiming to control) fellow people and their environments (Stirling, 2019).

What is significant about the criteria suggested by all these different qualities is that they offer means by which societies can hope to be more responsible in steering research or innovation in certain specific directions rather than others. This is important because, if efforts are not made to emphasise these broader qualities in policymaking, then research and innovation in particular sectors (like food, health, energy, transport, information, automation or security) will tend to be steered in directions favoured by whatever happen to be the most powerful incumbent interests acting most directly to shape research and innovation in particular sectors (Stirling, 2008). Experience shows that it cannot automatically be expected that these incumbent interests on their own will necessarily always prioritise wider social values or the public good (Gee et al., 2013; Harremoës et al., 2001). In ways that are inevitably subject to political tensions, then, practices and institutions of responsible research and innovation are widely seen to help enable to rebalance existing asymmetries of power and privilege in the steering of innovation (Nuffield Council on Bioethics, 2012).

5.7.10 Democracy

A final important and widely-discussed dimension of good practice in the conduct of policy for (or informed by) science is related to — but distinct from and complementary to — all the other criteria reviewed here: democracy (Jasanoff, 2005a; Stirling, 2014a). Again, this particular term can stand for a range of variously-discussed qualities in policymaking relating to other issues discussed here, as well as issues of accountability, representation and institutional design (M. B. Brown, 2009). Often neglected in discussions of scientific assessment as well as research and innovation, democratic capacities of multiple kinds are perhaps, in the end, the single most important consideration in determining whether the outcomes of science, technology or wider policymaking can be considered positive or negative (Ezrahi, 1992; Winner, 1992).

No matter what progressive qualities may be aimed at (or claimed) within a given policy process (like all those discussed here), their efficacy and sustainability (as well as crucial opportunities for interrogation) will depend on the broader qualities of democracy that prevail in the wider political environment (Kitcher, 2001). It is in this regard that an especially unfortunate misunderstanding comes to the fore: that respect for expertise, the prioritisation of science or the pursuit of analytical rigour are each in some way necessarily in tension with democracy (Jasanoff, 2011b). Of course, the details of such questions depend on the particular notions of democracy that might be entertained. If the term is simply used as a code for current imperfect political practices, then many questions will naturally arise. Yet if democracy is understood in a fundamental general sense as referring to 'access by the least powerful to the capacities for challenging power' then it can become clear that science itself is not only not in tension with — but deeply dependent on — such conditions (Stirling, 2014b).

It is exactly these kinds of constituting aspiration in the production of knowledge, after all, that arguably characterised the emergence of scientific cultures themselves out of the oppressive dogmatism of early modern monarchies and religion (Ezrahi, 1990). As the seventeenth-century motto of the British Royal Society has it, for instance, it is a constituting principle of science that knowledge is at its most robust if it is produced as freely as possible from overbearing authority ('nullius in verba') (M. B. Brown, 2009). Even if not always fully realised, it is foundational to science (as distinct, for instance, from religious or political social movements) that knowledge is most robust if it is open to experimentation, interrogation, argumentation and validation in ways that are free from relations of wealth, power or privilege (Stirling, 2011). In the end, the importance of democracy (of whatever continually-questionable kinds) is not a separate possible self-evident public good, but arguably the single most important guarantor of rigour and robustness in policymaking on (or informed by) science (Felt et al., 2013).

5.7.11 Implications

Appropriate designs for expert scientific policy advisory processes and policymaking for science are as subject to divergent contexts and perspectives as their contents; and so therefore just as irreducibly partly political. Nonetheless, extant literatures on this topic from many perspectives, illuminate some clear guiding principles; accountabilities under which may confidently be held to increase the general robustness of science advice. Broad guiding principles explored here include: trustworthiness: independence; transparency; inclusiveness; accessibility; responsiveness; deliberation; rigour; precaution; responsibility and respect for wider democracy.

5.8 POSSIBILITIES: THE EUROPEAN LANDSCAPE FOR SCIENCE ADVICE

In 1975, the European Union began a process of 'agencification'. Currently, there are over thirty European agencies that operate in, and often regulate, a multitude of policy fields such as food safety, pharmaceuticals, law enforcement, air safety, border control, telecommunications, financial supervision, etc. (Busuioc, 2014). Intensification of agencification occurred in the aftermath of multiple food crises (mad cow disease/BSE, dioxin contamination) in the hope it could restore the lost trust in the European Commission as a credible regulator (Busuioc, 2014). Examples are the European Medicines Agency (EMEA), the European Food Safety Agency (EFSA), the Office of Harmonisation in the Internal Market (OHIM), the Community Plant Variety Office (CPVO), the European Aviation Safety Agency (EASA) and the European Environment Agency (EEA). The main idea was that agencies were needed to inject neutral technical expertise into the EU regulatory process (van Ooik, 2005). Agencies are supposed to work in a way that is free of all political influence (Busuioc, 2009, 2014). Van Ooik (2005) noted that:

> *‘Most founding acts expressly stipulate that the agency concerned will be completely independent from the makers of law and politics. The agency’s output may and should not be influenced by political considerations’.*

As the Global Science Report (Organisation for Economic Co-operation and Development, 2015) points out, advisory institutions are also involved in providing scientific advice at a regional level. Apart from the agencies mentioned above, the Joint Research Centre (JRC), which consists of seven research institutes, provides science and technology policy advice and technical advice to the European Commission, the European Parliament and potentially also European governments.

Looking across the current European landscape regarding the provision of scientific evidence within decision-making, it is apparent that — apart from the EU’s agencies and the European Commission’s own JRC — there are multiple knowledge providers,including publicly-funded research institutes, universities, national academies, industrial research facilities, and expert advisers of different kinds. To these established sources of knowledge and expertise can be added other institutions and actors: member-based organisations (birdwatchers, anglers and beekeepers, environmental groups, special interest groups of various kinds with expert knowledge on specific matters), consultancies and think-tanks, campaigning groups, citizen science bodies and similar. In addition, there are numerous databases, information sources, websites and reports available in direct electronic form (Nowotny et al., 2001).

In term of governance, citizen science may be instigated by public institutions, such as natural history museums or university departments, both of which are subject to norms of accountability and transparency; or they may be instigated by special-interest groups that are not obliged by such norms (Alan Irwin, 1995). As such, citizen science projects offer evidence of how different governance structures shape, and are shaped by, the policy-science nexus when it is extended (Alan Irwin, 1995).

The advice ecology may also involve citizens in handling problems or acting on policy results. For example, such processes are found when citizens engage with a local museum or library as guides or learning ambassadors in order to alleviate cuts in public spending or to help advance new cultural policies. Such forms of cultural citizenship act as catalysts of insights that involve dialogues in situated practices and across differences of opinion (Dahlgren, 2006, 2009). These practices go beyond information on immediate political decisions. Their modes of involvement and collaboration help deepen citizens’ understanding of policy implications, and they widen citizens’ contexts of interpretation and networks of action (Louv, Fitzpatrick, Dickinson, & Bonney, 2012).

A survey carried out as a part of the project of Global Science Forum (Organisation for Economic Co-operation and Development, 2015) indicated that different countries have a variety of bodies and structures that provide scientific advice to political authorities (typically national governments) or societal actors. Often, they do not have a clear understanding of their role and responsibilities. The actual role of scientific bodies depends on how the scientific advisory system works as a whole. This makes it complicated to establish universal best practices and guidelines, especially when so-called 'grand challenges' are considered. In addition, the various bodies and structures are subject to quite frequent changes coming from political priorities and so-called social dynamics (Organisation for Economic Co-operation and Development, 2015).

In the case of 'grand challenges', which are by definition transdisciplinary, international advisory mechanisms operate via the existing intergovernmental organisations, such as the WHO, OECD etc., and bodies such as the IPCC and IPBES, which provide advice on a global scale, including climate change, energy, food security and disease epidemics. One should stress that the role of these structures is not particularly to provide policy advice to governments, although often the results of their reports are considered as such (e.g. Shaw & Robinson, 2004).

For a long time, quite independently and in parallel, international institutions representing the scientific community via organisations such as the European Academies Science Advisory Council, Inter-Academy Council and International Council for Science have provided scientific advice via a more bottom-up process. It is time to link formally these processes. The SAPEA project is in a step in this direction, but there is room for improvement at the level of the European Commission.

First of all, there is no clear relationship or dependence between the Joint Research Centre and the Group of Chief Scientific Advisers. Secondly, the Board at the Presidency is well advised to coordinate and direct the main questions which require scientific opinions, between advisory bodies of scientific communities at national and international levels (academies, universities) and the institutes of the EU Research Centre. It should be pointed out that the formal structure (the Joint Research Centre is supervised by the Commissioner for Education, Culture, Youth and Sport) and the existing Board of Governors of the Joint Research Centre are not helping in this coordination role. One may also consider establishing an independent European ethical expert group dedicated to optimising the structure, procedure and format of proving scientific expertise and advice to European policymaking bodies (the expert group is, of course, aware of the European Group on Ethics in Science and New Technologies (EGE)).

On the one hand, the diverse European advisory ecosystem sketched above creates a tremendous resource for policy and decision-making. On the other, there are clear questions of the reliability, independence and overall quality of technical evidence across such a range of sources (many or even most of which combine technical expertise with a particular perspective or interest). This in turn creates challenges for the communication of scientific evidence to policymakers (Bucchi & Trench, 2008).

Certainly, one important dilemma concerns the requirement both to be open to the broadest range of advice (including contending or contradictory opinions) and to avoid either 'information overload' or a simple 'lowest common denominator' effect (where different sources effectively neutralise each other). This is a general problem for science communication (S. R. Davies & Horst, 2016).

A further point in this context is that many scientists do not consider their expertise to be fully taken into account within policymaking (Pelkonen, 2018). One obvious example here is the area of climate change, where scientific frustration about the form and direction of policy is frequently expressed. A survey in Finland of researchers, civil servants, and politicians, i.e. active stakeholders and experts in the sphere of environmental knowledge and decision-making, recently reported that 75% of respondents disagreed with the statement that 'scientific knowledge is currently well taken into account in decision-making' (Pelkonen, 2018). There may be many explanations for this. However, it is hard to avoid the implication that there is room for improvement in the communication of scientific advice to policymaking.

5.9 THE LANDSCAPE OF SCIENCE ADVISORY MECHANISMS

A 2018 special issue of the journal *Global Challenges* focuses on so-called scientific advisory committees (SACs). A SAC is defined as a group of individuals with relevant experience that provides advice to decision-makers, based on research evidence from the natural or social sciences. Instead of 'committee', some use the terms 'body' or 'panel'. Instead of 'scientific advisory', some use terms such as 'expert', 'technical' or just 'advisory' (Hoffman et al., 2018).

The literature on SACs and their effectiveness is limited and scattered, as it is still at an early stage. Most work is in case studies or opinion pieces (Hoffman et al., 2018).

Røttingen and Ottersen (2018) suggest that there is a general trend towards systematic reviews of the available evidence and away from expert groups, on the basis that it would seem to strengthen levels of transparency. However, they suggest that many of the complex policy questions need a combination of both systematic reviews *and* deliberative processes. Scientific deliberations within SACs are therefore often a crucial part of a system to provide evidence-informed policymaking.

Campbell and Pedersen (2015) referred to knowledge regimes in describing institutional arrangements for SACs. They compared different formats of science advice to policymaking in the US, France and Germany. The analysis revealed that the institutional settings are deeply embedded in the political culture of each country, and that national styles of regulation and policymaking lead to different structures and formats for feeding expertise into the policymaking process. The US adversarial style, the German cooperative style and the French fiduciary style of policymaking assign experts different roles in the advisory systems and provide also different arenas for non-experts to be involved (R. E. Löfstedt & Vogel, 2001; O'Riordan & Wynne, 1987). The main result of regime comparison has been that there is not a single best mechanism or format that optimises science input to policymaking, but that the effectiveness, efficiency and fairness of advice depends on political culture and the topical context in which the advice is articulated. This also includes different forms of cooperation between scientific experts, professionals in the field, stakeholder groups and affected public. If there is a general conclusion that can be drawn from the literature, it is that the formats of organising science advice should be flexible, responsive to the needs of the policymakers, inclusive in the sense that different epistemic communities are represented, and clearly mandated to provide focus and legitimisation for what is demanded; in short, institutional learning by variation (Listokin, 2008).

Types of scientific advisory bodies

A described landscape of SACs helps researchers and policymakers understand the wide variety of designs that SACs have taken in different contexts. It is important to provide policymakers with the tools and evidence to design effective SACs in their particular context (Groux, Hoffman, & Ottersen, 2018).

A number of countries, regions and international bodies have established SACs and similar mechanisms. Their experiences were summarised by Wilsdon, Allen and Paulavets (2014), who concluded that across national governments and international bodies, there is a variety of structures and institutions for scientific advice. 20 draft national/regional case studies were drawn up to profile different advisory systems[4], plus 3 international bodies[5] and 3 sets of principles[6] by which to strengthen science advisory systems.

Hoffman et al. (2018) suggest the following variations across SACs, distinguished by type of adviser, type of structure and type of user.

TYPE OF ADVISOR	TYPE OF STRUCTURE	TYPE OF USER
THEMATIC FOCUS: HEALTH VS OTHER AREAS	FORMALIZATION: STATUTORY VS INFORMAL	REPORTING: INTERNAL VS EXTERNAL (RELATIVE TO USER'S INSTITUTION)
GOAL: ACTION-ORIENTED VS ASSESSMENT-ORIENTED	DURATION: PERMANENT VS TEMPORARY	JURISDICTION: WITHIN A SINGLE COUNTRY VS ACROSS COUNTRIES

Table 4. Dimensions of variation across SACs and examples (Hoffman et al., 2018)

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[4] Australia, Canada, China, Cuba, El Salvador, Finland, France, Germany, India, Italy, Japan, Mongolia, New South Wales, New Zealand, Quebec, Switzerland, South Korea, South Africa, Taiwan, UK

[5] UN Scientific Advisory Board, the International Council for Science, Future Earth

[6] UK GO-Science, Science Council of Japan, Sir Peter Gluckman (CSA of New Zealand)

Table 5 describes and compares the 3 comprehensive typologies of SACs uncovered by Groux et al. (2018).

Aspects of typology	Level of operation	Geographical scope	Broad categories studied	Focus
(Glynn Steven, Cunningham, & Flanagan, 2003)	National, Regional	European: EU15 states and EU itself	• General: users, policy areas, and status of advisory bodies • Structural: secretariat and membership of advisory bodies • Functional: Scope of work, independence, transparency, generation, delivery and responses of advice, changes in the advisory system	To systematically map and characterise significant scientific advisory bodies in Europe
(Schulz, Bressers, van der Steen, & van Twist, 2015)	National	European: France, UK, Germany, Sweden, Netherland	• Configuration: size and temporal orientation • Administration: regulation, financing and obligations for government • Composition: how advisory systems are manned • Political administrative regimes	Identifying institutional elements of advisory systems and their political administrative regime setting
(Heinrichs, 2006)	National	Germany and the US	• Distance from politics • Policy function • Dealing with pluralism of knowledge, values and interests • Communication, interaction, inclusion	Orientation tool for assessment and optimisation of advisory structures

Table 5. Previously proposed typologies of scientific advisory committees (Groux et al., 2018)

The authors propose a new global typology:

Characteristics	Options for the characteristics
Sector	• Health • Environment • Education • National security • Justice • Energy and transportation • Other
Level of operation	• Supranational • National • Subnational
Permanence	• Timelimited • Standing
Target audience	• Internal • External
Autonomy	• Armslength • Embedded
Nature of advice	• Descriptive • Prescriptive

Table 6. Proposed typology of scientific advisory committees (Groux et al., 2018)

The authors apply the new typology to a set of selected SACs:

Name	Sector	Level of operation	Permanence	Target audience	Degree of independence	Nature of advice
IPCC	Environment	Intern.	Standing	External	Embedded	Descriptive
EASAC	Energy, biosciences, environment	Intern.	Standing	Internal	Inbetween	Prescriptive
CCA	Interdisciplinary	National	Mixed	External	InBetween	Descriptive
Puget Sound WQA	Environment	Sub national	Mixed	Both	Embedded	Descriptive
GESAMP	Environment	Intern.	Standing	External	Armslength	Mostly descriptive
STAP	Environment	Intern.	Standing	Internal	Inbetween	Prescriptive
Defense Science Board	National security	National	Standing	Internal	Embedded	In determinate
Health Canada	Health	National	AdHoc	Internal	Inbetween	Prescriptive
WBGU	Environment	National	Standing	Internal	Armslength	Prescriptive
UNSCEAR	Energy	Intern.	Standing	External	Inbetween	Descriptive

Table 7. Characteristics of selected SACs (Groux et al., 2018)

Setting up a SAC

Hoffman et al. (2018) suggest that there are six stages for the establishment and operation of SACs:

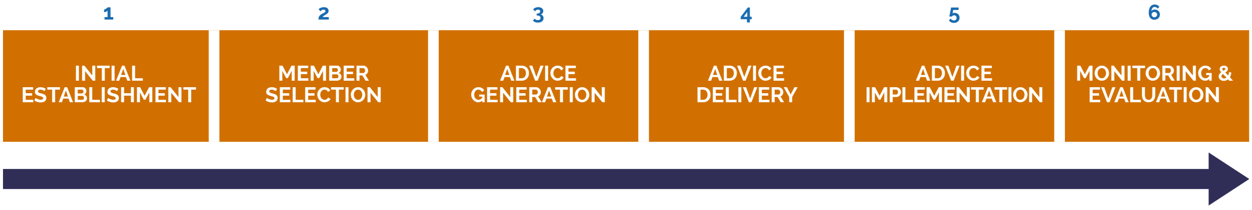

Table 8. Dimensions of variation across SACs and examples (Hoffman et al., 2018)

When a government or other form of administration is considering establishing a systematic approach to science advice, Røttingen and Ottersen (2018) suggest there are four aspects that need to be addressed:

- *Sector-specific or cross-sectoral?* Should there be specific SACs set up for each sector, or one common mechanism for all sectors, or a combination? A number of countries have robust science advice functions for specific sectors (for example, economic policy, public health, food safety, environmental issues, security, energy etc.). However, many of the current societal challenges are multi-sectoral and therefore require transdisciplinary insights and analyses. A cross-sectoral mechanism can enable collaborative learning.
- *Policy content or policy process*? Should the SACs provide input on policy *content*, or the policy *process* (i.e. how to use and integrate research evidence in policymaking) or some combination? The ability to analyse and assess specific scientific issues requires adequate insight and expertise and a strong support (secretariat) function that can prepare research syntheses and other documents for the committee.
- *Policy for science?* What should the role of the SACs be in policy for science? There is a potential role for demonstrating the value of research in society and promoting public engagement in science. A content-related role often identifies research gaps and the need for new research.
- *Relationship to government?* How independent or dependent should the SACs be? Most people argue strongly in favour of independence as the means to secure legitimacy. At the same time, SACs need to get their mandate and work programme from government in order to secure buy-in. Striking such a balance is not easy; it requires careful judgement and opportunities for building trust and relationships.

The authors argue for a 'supra-SAC' that focuses on process, working with sector-specific mechanisms for science policy that is independent from government, whilst also depending on it (Røttingen & Ottersen, 2018).

The effectiveness of SACs

The ultimate goal of SACs is commonly seen as informing subsequent decisions with the best available research evidence, with the aim that positive impact is maximised and any negative (often unintended) consequences are minimised (Hoffman et al., 2018). The authors argue that there are potentially three related determinants for the effectiveness of advice from SACS and indirectly the effectiveness of SACs themselves: these are *quality, relevance* and *legitimacy*. The definitive indicator of a committee's effectiveness is whether it informed subsequent policymakers' decisions. Yet it can also be useful to study the effectiveness of SACs by examining their outputs (i.e. the advice they provide) and outcomes (i.e. behaviour change among relevant decision-makers). The authors suggest a number of determinant features for the effectiveness of SACs:

Determinant type	Determinant of effectiveness
NATURE OF THE SUBJECT MATTER	Thematic focus (e.g. health, environment, education) Generality Complexity Scientific controversy Public controversy
NATURE OF THE CHIEF ACTORS AND THEIR RELATIONSHIP	Nature of the user of the advice • Level (e.g. local, national, international) • Role (e.g. clinician, manager, politician) Nature of the committee • Formalisation (e.g. statutory vs informal) • Duration of operation (permanent vs temporary) • Size • Competence of members (e.g. type, level, diversity) • Representation (e.g. diversity in gender, age, area of residence) • Remuneration Nature of the committee-user relationship • Integration of committee (internal vs external to user)
PROCESS STAGES	Establishment of the committee • Entity establishing the committee • Process leading up to the establishment Committee member selection • Management of conflict of interest • Democratic selection Advice generation • Existence of guidelines for the decision-making (e.g. code of practice) • Leadership resources (e.g. time and financial) • Type of evidence assessed • How evidence is accessed • Decision-making rule (e.g. consensus vs majority vote) Advice delivery • Mode of communication with user • Scone of dissemination (public vs private) Advice implementation • Decisions on optimal use of advice Review • Monitoring and evaluation of committee • Feedback loop for reform of committee
CROSS CUTTING	Transparency, openness, and publicity Accountability Independence from user, political, and financial influence Approach to risk and uncertainty

Table 9. Determinants of effectiveness (Hoffman et al., 2018).

Behdinan et al. (2018) undertook an extensive overview of systematic reviews that aims to inform which institutional features of SACs maximise their effectiveness. Disappointingly, nearly all the useful systematic reviews focused on the health sector and overall there was a lack of high-quality systematic reviews (the authors chose six). Based on the systematic review undertaken, the overall effectiveness of SACs would appear to be a function of:

1. *The way the input of the group members is aggregated.* In Murphy et al. (1998)'s review of 177 studies, they state that the aggregation of group output is determined in two stages: firstly, the importance given to the contributions of individual participants; and, secondly, the assessment of the group's level of agreement, based on their contributions, regardless of the importance given to each of them. Murphy et al. suggested that voting is preferable in situations that require ranking between options; voting was not recommended for normative judgements. The authors suggest that voting itself has been found to be contradictory in some cases (for example, it can lead to the formation of alliances) and suggest the evidence is inconclusive when it comes to assessing the benefits of weighting by expertise.

2. *The inclusion of inputs from the public*; a large qualitative literature argues in favour of public input into the work of expert panels.

3. *Asking several individuals to independently assess the same body of evidence*, with a view to controlling for bias.

The synthesis of the evidence pointed to several key themes. These were: a moderate group size; a multidisciplinary group composition; established group protocols; and sufficient training and communication.

- *Size*: while no specific committee size was reported consistently by the systematic reviews, it is recommended that SACS be composed of around 6–12 members to ensure that both representation and communication of unique perspectives are achieved.
- *Diversity*: SACs should reflect different specialties, as well as diversity in demographic characteristics, expertise and initial views on the subject matter. There was found to be a lack of generalisable evidence on how group features influence the recommendations proposed by a SAC.
- *Procedural determinants*: it is recommended that the SAC structure be maintained through clear protocols, which set out specific responsibilities, a structured group format and a well-defined framework for the task.
- *Communication*: communication, particularly with regard to training and facilitating cohesion between committee members is vital. Training and support on appropriate communication, the presence of a supportive chair, clearly outlined objectives and group processes should be provided to SAC members.

Chapter 6: Lessons learned

6.1 BASIC INSIGHTS FROM THE REPORT

In light of major worldwide transformations such as globalisation, digitalisation and sustainable development, scientific policy advice faces new challenges and targets (Dryzek & Pickering, 2018). These major transformations are accompanied by massive social and environmental impacts, changes of trade and cultural lifestyles, an increased pluralism of positions, values and claims, the erosion of trust and confidence in governing bodies, an increased public pressure for participation, and growing tendencies towards polarisation between fundamentalist value groups and advocates of progressive change (K. Brown, O'Neill, & Fabricius, 2013). The resulting conflicts puts pressure on political systems to integrate different outlooks and visions of the future and to provide justifications of governmental decisions on the basis of both scientific evidence and values. In other words, sound evidence is a major catalyst for collective decisions needed for modern societies to advance politically and economically (O'Brien, 2012).

In this situation, policymaking institutions are in urgent need for scientific advice, which is supposed to provide background knowledge, to help policymakers to understand the impacts of their decision options, to compare strategies to reach predefined goals and to offer assistance for resolving the conflicts and tensions that arise in the course of the transformations ahead of us (Organisation for Economic Co-operation and Development, 2015). Concepts such as transformative, transdisciplinary or co-creative approaches to inform policymaking elucidate the direction in which scientific advice finds its new role(s) (Wittmayer & Schäpke, 2014). Based on the discussion of these concepts, this report has provided a review of the conceptual and empirical literature on the science-society nexus. Research on advisory processes indicates that the following points are important to stress:

- **There is a need for anticipation of human interventions in the Anthropocene era**. Using scientific expertise in the policy arena is one element in the quest of modern societies to replace or amend the collective learning process of trial and error by the more humane method of anticipation, in which the possibility of painful errors is reduced (German Advisory Council on Global Change, 2000). This process is socially desired, but it cannot reduce to zero the uncertainties that result from change. Anticipation and resilience are both necessary means to cope with future events and challenges. Yet they cannot replace uncertainty and ambiguity of predictive knowledge, in particular if the topic is complex and the problem of sophisticated and complex (so-called 'wicked') problems. Scientific advice can help to anticipate future challenges and problems and assist in designing coping strategies or interventions for preventing, reducing, mitigating or compensating potential harm to society. There are short, medium, and long–term political decisions to be taken by politicians and all may need scientific advice to strengthen and adapt them to the local and global reality that societies face. In a world in which human actions have become the dominant force in shaping the world (Anthropocene), this function of anticipating the effects of human interventions on global sustainability places a strong mandate on the scientific communities to generate, collect and review the best available knowledge to help design these crucial interventions (Dryzek & Pickering, 2018).

- **The focus of scientific advice must be critical review of the available evidence and its implications for policymaking.** The policymaking process and related decisions made by policymakers should be evidence-informed but the scientific advice itself must always be evidence-based. Robust scientific evidence, obtained through systematic research and evaluated according to established methodology and rules, is essential for understanding complex natural, technological as well as social phenomena and, therefore, for making informed decision. To ensure sustained influence on policymaking it is important that scientific advice is based on evidence that is respected as valid, relevant and reliable (and in many disciplines replicable), and that it includes a quantitative assessment or, if that is not possible or feasible, a qualitative characterisation of scientific uncertainty and ambiguity. The need for the latter has been recognised for many years and some progress has been made, including by EU agencies that provide scientific advice. A recent review concluded that the EU agencies should share experiences while developing guidance and practices best suited to identify, address and communicate uncertainty based on their own needs and mandates (European Food Safety Authority, 2018a).
- **Scientific advice should not prescribe but inform policies.** Any political decision needs to consider the likely consequences of decision options (where scientific input is essential), as well as the social, political and moral desirability of these consequences (where plural values and ethical principles play a major role). In addition, it is not the role of scientific advisers to determine the level or quality of evidence that is regarded as sufficient for effective policy or good governance. In the end, any scientific advice may turn out to be incomplete, contested or even unsubstantiated. Within the domain of science, scientists unavoidably make normative decisions regarding, for instance, the standards of evidence required for accepting a particular claim or theory. In policymaking, however, policymakers must decide what level of certainty is required to act on scientific advice. Within the EU, the Precautionary Principle has been widely adopted. The Precautionary Principle justifies policy interventions in cases where scientific evidence of risk is insufficient, inconclusive or uncertain and there are indications through preliminary objective scientific evaluation 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 chosen level of protection (European Commission, 2000). Given these conditions for effective scientific advice, decision and policymaking must take into account additional forms and sources of knowledge beyond those obtained by science-based methods, as well as criteria for judging desirability and assigning trade-offs when competing values are addressed. In many cases, different explanations can account for the available facts, and the selection and interpretation of evidence must be guided by the articulation of different social values and legitimate interests, involving not only advisers and decision-makers, but also additional stakeholders and civil society.

- **The functionality and significance of scientific advice depends on issue and context.** The influence of expertise depends on the cultural meaning of expertise in different social arenas and cultural backgrounds. There is no right or wrong in choosing the most appropriate perspective for the role and function scientific expertise can play in policy- and decision-making. It depends on context and issue. If the topic is contested, expertise may conflict with public preferences or interests. In addition, policymakers and experts pursue different goals and priorities. One crucial question facing policy decisions is how to compare and rank knowledge claims generated through the methodologies of science against other forms of knowing. Prioritising policy informed by science at the expense of policy that draws on local and experiential knowledge can lead to accusations of 'scientism' or neglect of local concerns. It is, hence, important to acknowledge that scientific expertise cannot replace public input in the form of locally-relevant knowledge, historical insights and social values. There are many forms and sources of knowledge, beyond what is available through the various methods of scientific investigation. Scientific advisers are well advised to see their role as being an important and unique source of robust and reliable knowledge but not as an exclusive provider of knowledge for informing decision and policymaking. The degree to which scientific input is perceived, valued and appreciated within a political arena plays a major role for the practical influence and power of scientific experts in collective decision-making. It has been demonstrated that when policymakers and science advisers agree in advance on the role and function that scientific evidence should play in the respective arena, there is less room for misunderstanding and conflict (Lentsch & Weingart, 2011b).
- **Form *must* meet function when designing appropriate policy-science interfaces.** There is no universally applicable model for structuring scientific advice to policymaking. Recipes are not useful in designing the nexus between policymaking and scientific evidence. It is rather (a) the type or nature of available expertise and (b) the type of advice needed that should determine the procedure, structure and composition of the advising process. This requires first to characterise the knowledge that science can offer to policymaking for the respective issue and second the purpose of the advice. In principle, scientific expertise can serve five functions: enlightenment, orientation, integration, strategy building and co-creation. Each of these functions require different formats and procedures to ensure that the special contribution of scientific knowledge is given its appropriate place and role in the advice-giving process. All five functions are in demand by policymakers but may also distort their perspective on the issue or prescribe a specific framing of the problem. That is why many policy analysts demand that scientific input is controlled by democratic institutions and open to public scrutiny.
- **Scientific advice to policymaking provides a plurality of legitimate perspectives and insights.** Defining 'the issue' and the selection of the most appropriate expertise requires judgement and vision. Scientific advice is always related to the social, political and moral context in which it is enacted. Such a context is driven by values, interests and preferences of actors. Yet scientific evidence should not be another expression of a special interest group, called scientists, but should represent insights and claims about causal or functional relationships between human actions (interventions) and expected effects. The

line between cause and effect is often complex, uncertain and ambiguous. This means that in general there is more than one possible answer to a scientific question. Much of the evidence presented by scientists is contested, laden with uncertainties and reliant on specific assumptions. It is therefore essential that, for complex problems and issues, the complete variety of scientific opinions is represented and all the uncertainties and ambiguities are fully disclosed. More specifically, the following lessons can be applied to dealing with complex scientific topics:

  - It is essential to involve the widest range of participants covering the full range of relevant perspectives
  - It should start with a deliberative phase to explore different framings of the problem and agree on which framings (plural if needed) will be considered for analysis
  - Within each framing, it may be helpful to try to identify parts of the complex problem where specialist input could be useful and, as far as possible, frame the questions for those parts in a well-defined manner
  - In the analytical phase, different parts of the problem can be addressed by relevant specialists, using methods appropriate to each part. For those parts that can be framed as well-defined questions, it may be possible to express the impact of uncertainties by using probabilities or other means of characterising uncertain outcomes; other ill-defined questions may demand more narrative descriptions of uncertainty. However, regardless how uncertainty is framed, the sources of uncertainty should be described (NUSAP is one of the options for this) and their impact should be characterised clearly and the evidence and reasoning for it should be explained.
  - The analytic phase should feed back into the deliberative process, or be followed by a second round of deliberation, where the assessments or advice on the different parts of the problem are integrated

- **Scientists as well as policymakers should be sensitive to the effects of heuristics, biases and frames.** These mechanisms of drawing inferences from data and information may be cognitive, affective, interest-related or value-based. To cope with biases and conflicting interests, some proven essential features are transparency about each participant's prior commitments to special causes or interests; a vigilant acknowledgement of and attentiveness for potential cognitive and affective biases; and a moderating team with special communicative skills. One should be aware, however, that individuals or groups may be unaware of their biases or convinced that they are purely 'objective'. One of the positive effects of having access to different disciplinary perspectives is that this plurality can act as a check-and-balance procedure to test disciplinary presumptions and norms that may themselves introduce unintended bias. Often, institutional attempts to deal with bias are rather clumsy; as Onora O'Neill has argued, they do little to increase trustworthiness and might even have the overall effect of reducing trust in expert institutions (O'Neill, 2002). Nevertheless, being attentive to potential heuristics and biases is an important element of the reflections that should accompany scientific advice to policymaking.

- **Science advice is always affected by values, normative conventions and preferences.** Value judgements are present at different levels and stages of scientific decision-making. At the most fundamental level, scientists take positions when they pursue a particular scientific project or when they assign specific weight to available evidence in accepting a particular scientific theory. These choices are informed by cognitive as well as social values. Scientists also make value judgements in choosing research topics and goals, in staffing their research projects, for instance, in using students or excluding certain categories of researchers (e.g. women or non-whites), when dealing with the use of human subjects and animals, in their choices of the methods for dissemination, and in applying research findings. Furthermore, as soon as policy issues and problems are addressed, they are embedded in a web of knowledge, values and interests, all of which are often closely intertwined and it is hard to distinguish between 'evidence' and 'values'. Rather than highlighting the role of objective knowledge provider, the science-policy nexus is better served when both sides are transparent about what values and goals they apply and how knowledge claims are selected, processed and interpreted. This creates more trust and confidence in the institutions and processes for including scientific advice in policymaking.
- **The effectiveness of scientific advice depends on the right composition of advisers and the quality of the dialogue between advisers and policymakers.** Scientific advice has to include evidence that clarifies and elucidates the factual content of an issue, including a characterisation of its robustness and validity, but also the ethical and societal impacts of the topic and the values involved. When translating evidence and research findings, it is of crucial importance that issues such as transparency, openness, assumptions and uncertainties in scientific conclusions are addressed and communicated. The advisers should accept some level of responsibility in advising and in the implementation phase of their advice. A (real-time if possible) feedback on the effects of advice is needed, that can be used for effective adjustments or corrective actions during its implementation. This implies that, when technical or natural science expertise is requested, it is useful also to have social scientists and representatives of the humanities at the table. They can offer important contextual insights into the problems and point to behavioural or social implications of what is discussed or planned.
- **The relationship between science advisers and policymakers relies on mutual trust.** Sometimes expert advice is not trusted because the questions that the experts have addressed are regarded by various stakeholders or policymakers as the 'wrong ones' (i.e. not those that are really causing concern). It is notable, too, that some of the most important shifts in environmental policy over the last half-century (the move from sectoral to more integrated pollution control, for example) came about when 'the problem' itself had been reframed. Nor can we always tell, in advance, whether the effects of advice will be direct or indirect, immediate or time-lagged, attributable or 'atmospheric' (James, 2000). As the case of the UK RCEP shows, expert advice can have effects that were not intended by those who commissioned it! It is, therefore, important to maintain a capacity for 'frame reflection', as well an openness on the part of political actors to disruptive advice.

- **The most highly recommended science advice process combines analytic rigour with deliberative argumentation.** Advice to policymaking should follow the model of an analytic-deliberative process (Curato et al., 2017; Forester, 1999; P. C. Stern & Fineberg, 1996). The analytic component of such a process refers to the inclusion of systematic and peer reviewed knowledge. Systematic expertise is regarded as an essential resource for obtaining and utilising the background knowledge necessary to understand the complexity of the issue under consideration and to anticipate the impacts of various policy options. The second component, deliberation, refers to the style and procedure of exchanging arguments and reaching evidence-informed and value-balanced conclusions in a discussion. For a discussion to be called deliberative, it must rely on mutual exchange of arguments and reflections rather than on decision-making based on the status of the participants, sublime strategies of persuasion or socio-political pressure. Deliberative processes include a debate about the relative weight of each argument and a transparent procedure for balancing pros and cons. Many formats for designing and structuring analytic deliberative formats are being discussed in the literature: one of the most promising procedures for such a format is the model advocated by the US National Research Council (National Research Council, 2008; P. C. Stern & Fineberg, 1996).
- **Within an analytic deliberative process, stakeholders and citizens should be integrated.** Science advice should not be seen as a one-off activity but should foster continuous forums for deliberation between scientists, the public and policymakers. This is about the core values of democracy. Extending the advice beyond the science-policy relation by involving stakeholders and citizens as participants implies a number of considerations:
    - First, citizen and stakeholder participation must incorporate transparency of aims
    - Second, citizen and stakeholder participation must specify the means of power regulation for different actors
    - Third, citizen and stakeholder participation must develop responsive communication strategies that can act as levers of aims and means.

Some of the best catalysts in following and advancing these recommendations are institutions and networks that are guided by standards of public value and whose modus operandi are free of commercial and party-political considerations.

- **Science advice is not limited to political bodies, but includes science communication with stakeholders and society.** The effectiveness of the process of communicating scientific evidence and advice will obviously depend on the specific goal, as well as on the knowledge and experience of scientists and their audiences. In the particular case when science is communicated beyond the target audiences, i.e. policymakers, the primary objective is that relevant information is understood, including the full complexity and uncertainty, and used to make informed decisions. Effective science communication includes:
    - Clarification and elaboration about the quality of the evidence, including description of its robustness and reliability, and the associated social and ethical issues;

- Clarification about the treatment of uncertainties, and ambiguities and how different perspectives have been treated and integrated;
- Clarification about the possible alternative courses of action and the reasons for their non-selection;
- Clarification about the scientific advisers, their background and credentials based on meaningful, real-life achievements rather than on (mainly) image (rankings, scores, impact factors, etc.).

Taking into account that science communication is not a neutral process, an essential component of this exercise is building trust and credibility. To this end, a particularly effective approach is to form partnerships between scientists, policymakers and practitioners who implement policy decisions. By working together, scientists learn about local sources of knowledge, needs and specific goals, while those who make and implement decisions gain a better understanding of the complexities and uncertainties inherent in the creation and interpretation of scientific evidence. An important outcome is that the resulting policy is more evidence-informed, rather than the creation and selection of evidence being policy-based. Collaboration between scientists and people outside scientific institutions is also important in view of the growing interest of civil society in scientific advice, particularly in the case of 'issue-driven' science.

6.2 LESSONS FOR THE ORGANISATION OF SCIENTIFIC ADVICE TO POLICYMAKING ON THE EUROPEAN LEVEL

The review of different concepts, approaches and formats for organising scientific advice to policymakers produced a large variety of insights, observations and normative conclusions. There is no single best way to provide scientific advice to the various European bodies of policymaking. It is advisable to see this plurality of approaches as an advantage rather than a problem. However, there are some crosscutting lessons that can be learned from the many evaluations and empirical studies of the nexus between scientific advice and policymaking, in particular at the European level.

- **Need for multidisciplinary composition of European advisory bodies.** It has proven useful to convene a multidisciplinary team of experts when giving advice to policymakers on all levels, but specifically on the aggregate European level. Most policy questions touch upon more than one (disciplinary) knowledge domain and require advice from different disciplines and perspectives. This quest for plurality can be an orientation when looking for stakeholders or representatives of various affected publics in policy settings in which special knowledge or expertise outside of academia is needed for dealing with the problem or question at hand. The evidence suggests that presenting insights from different disciplinary (and other) perspectives can result in 'frame reflection' and increased robustness in the advice offered. However, there is an important difference between 'a committee of experts', however broadly based, and a committee including stakeholders'; both have value but they serve different objectives.

- **A suitable role model for comprehensive advisory mechanisms in Europe is the concept of analytic-deliberative policy**. The analytic component selects and evaluates the evidence available to understand a problem or to design various policy options, while the deliberative component provides a discourse with scientists and stakeholders on how this evidence should be interpreted given the political context, the diverse values and the various interests. In terms of institutionalisation, one could design either nested processes of linking scientific advice with deliberation in various circles such as stakeholder forums or open public debates or, more formally, to establish a two-tiered process of collecting and evaluating the evidence by experts and organising a larger forum with stakeholders and representatives of the affected public to reflect upon the implications of the evidence presented.
- **Emphasis on capacity building**. A precondition for providing evidence-informed advice to decision-making is institutional capacity building. This is necessary in order to recruit the best expertise from all countries in Europe. National institutions such as the academies of sciences need sufficient resources to support academics that take up roles as experts, e.g. by initiating institutional incentive and reward systems. National as well as European institutions need to secure the necessary formal conditions that rules for scientific integrity and codes of conduct are in place that provide sufficient proof for disinterestedness and trustworthiness of the advice that is given to policymakers. These policies and codes could include guidelines for setting up contractual agreements between policymakers and scientific experts or the institutes from which they come.
- **Establishment of ethical codes for assuring high ethical standards.** With regard to the quality control of science advice for policymakers, SAPEA has already issued important guidelines on advising policymakers and society and procedures for quality assurance of scientific advice (Science Advice for Policy by European Academies, 2017). The quality of a report designed for a policy decision-maker depends on the composition and the skills of the expert group. This quality concerns the information given and the understanding of this information by the policy decision-maker and his/her advisers. To ensure continuous quality control on ethical issues, ethical committees are needed for guiding scientific advice to policymaking. The European Academies could act as forums for preparing a list of ethical guidelines for the structuring of scientific advice bodies and the selection of members. One should also consider striving for an international agreement on the best practices to include ethical and societal questions in the development of the science-policymaking interface.
- **Need for an agreement on recruitment and operational rules and rights**. The analysis of the impact of various policies on the different aspects of human life may necessitate scientific skills from a variety of disciplines: economic, sociological, judicial, medical etc. All European countries, as well as the European Commission, would be advised to place most emphasis on an interdisciplinary composition of advisory bodies, be they temporary or continuous. In order to assure high quality and high ethical standards, the recruitment of the participants of advisory groups needs to be conducted, or at least confirmed, by respected scientific entities such as national science academies or national science foundations. Each member should disclose his or her prior involvement in the topic of discussion

and potential interests. It is not necessary to exclude experts with special interests as long as these interests are made transparent. Furthermore, the expert bodies need to have a written set of clear rights and obligations, which assure their independence, the right to publish even without the consent of the advisees, and special rules for how to reach agreements and how to communicate to the various audiences. The Berlin-Brandeburg Academy of Sciences has issued a white paper that articulates and specifies the internal and external rules for science advice committees (Lentsch & Weingart, 2011a). Furthermore, there is a need for better quality control of the comprehensiveness and readability of the experts' reports. This requires awareness of the providers and users of science advice, but may also involve mediators who translate scientific data, information and knowledge for non-expert audiences. The mediator's role is to clarify and summarise scientific knowledge. This role could also be taken up by the offices of the chief scientific advisers appointed by governments or ministries or national academies consisting of scientists and scholars.

6.3 SCIENCE-POLICY-SOCIETY INTERFACE WITHIN A EUROPEAN FRAMEWORK

With regard to the presentation and communication of scientific advice to policymaking, a number of specific issues need to be addressed. First, there is a particular need for 'knowledge brokers' who can operate credibly in this context. Possible brokers in Europe include national scientific academies, chief scientists, special committees and advisory groups. Often scientists from different disciplines can play this role, as they understand scientific reasoning but are not experts in the topic under review. It is crucial that such brokers can take account of the breadth and diversity of evidence sources, rather than simply presenting scientific evidence from their own disciplinary perspective; this may require that brokers work collaboratively rather than separately for some questions.

A second issue concerns the need to build long-term relations when designing European bodies for advising policymakers. The relationship between scientific advice and policymaking is better understood as an evolving process than as a series of one-off encounters. This will of course also depend on the relative urgency and unexpectedness of the particular case or issue (some problems cannot be predicted). However, even unexpected or unusual cases still depend upon mutual expectations and understandings. In general, the relationship between scientific advice and policymaking is best seen as a matter of regular (even continuous) interaction, allowing social and scientific learning between the producers and users of expert knowledge. This can be a challenge in practice, as both knowledge providers and decision-makers face competing pressures on their time and resources. Consequently, it seems prudent to have at least one continuous body of scientific advice rather than a sequence of ad-hoc committees.

A third, closely related, issue relates to the traditional 'linear' model of scientific advice to policymaking. According to this, knowledge is communicated in one direction from experts to policymakers under protected conditions. In a complex knowledge and policy environment, it is better think of communication in more interactive and dynamic terms (Horst, Davies, & Alan Irwin, 2017; Jasanoff, 2004c, 2007). This in turn draws attention to some of the challenges of accessing expert knowledge, providing incentives to knowledge producers to make their expertise available and achieving knowledge synthesis. Such an interactive model also suggests the importance of achieving open and robust informational flow — even if it also raises logistical and organisational problems beyond those of 'getting the best experts into the room'. One way to accomplish this goal is to mandate the European science advisory bodies to play an active role of knowledge brokers towards the European public and to make sure that these bodies are technically and organisationally well equipped to perform such a task.

A fourth issue, and one raised very regularly, concerns the particular issue of scientific dissent and disagreement. The challenge here is to view legitimate expressions of disagreement and difference not as an obstacle to policymaking but as an important resource (Stilgoe et al., 2006). Indeed, scientific knowledge production is generally stimulated by disagreement, scepticism, attempted rebuttal and criticism — and openness is a key institutional norm of science. The question here is how to identify 'legitimate' challenge and from whose perspective this is to be judged. This would seem to require the skills of a range of disciplines, including the social science and humanities (Alan Irwin, 2008). Again, it makes sense to establish rules of how advisory bodies will deal with dissent (such as minority votes), how they will incorporate different scientific opinions and also other opinions, and how the discussion among the participants will be documented so the route to a possible consent and agreement is open to public scrutiny.

A fifth issue relates to the trustworthiness of advisory processes. One important principle here is that deliberate attempts to build trust can often produce the opposite effect as accusations of manipulation and 'PR' follow. A more positive approach is to consider the 'social robustness' of advisory systems. As Nowotny has expressed this, socially robust knowledge has three interrelated aspects: robustness is tested outside the laboratory as well as inside; social robustness is most likely achieved through an extended group of experts, users and 'real or "imagined" lay persons'; society is not only an 'addressee' but an 'active partner in the production of social knowledge' (Nowotny et al., 2003, p. 155). As pointed out in Section 6.2, such a requirement could well be addressed when designing the policy advice process in an analytic-deliberative format.

A sixth issue refers to the incorporation of citizens into the scientific enquiry and consultation process. The central role of evidence-informed knowledge for policy support extends beyond the science-policy nexus. In democratic societies, citizens are key agents in this knowledge exchange for two reasons. First, citizens are often the subjects of policymaking in terms of altered physical or political conditions or of socio-cultural practices. Second, citizens vote politicians in or out, and they pay taxes that help fund research at public institutions. Therefore, both policymakers and scientists are accountable to citizens and ultimately depend on their trust.

Developments in the early 21st century to involve science in addressing large, societal challenges deepens the need to extend the advice ecology to include public governance so as to secure public value for and by citizens. Extending the advice ecology to include public governance is an ongoing process that involves citizens in two capacities: in the process of creating knowledge and shaping problems, and in the process of handling problems or acting on policy results. In both of these capacities, citizens can play a more or less active and decisive role in relation to scientists and policymakers. Following a spectrum developed by the International Association for Public Participation (2014), citizen participation or engagement can be defined along a continuum as follows:

- Inform
- Consult
- Involve
- Collaborate
- Empower

At one end of the spectrum, scientists and policymakers provide citizens with balanced information to assist their understanding of the problem or the solution that the professionals have identified, be they scientists or policymakers. At the other end of the spectrum, citizens have the power to make decisions, not scientists or policymakers, whether in the identification of pertinent problems or the implementation of robust solutions. Both ends of the spectrum are likely to involve one-way communication from professionals to citizens (inform) or from citizens to professionals (empower) with no necessary or immediate feedback mechanism. Between these two ends is a range of engagement processes that involve forms of dialogue and negotiations across the scientist-politician-citizen triangle (S. R. Davies & Horst, 2016). Many formats have been developed for such an intensive interaction between citizens and scientists. It is essential that the rules for European science advice bodies include the possibility of organising and promoting outreach activities and active involvement of citizens.

Some mechanisms are already practised in Europe. They involve citizens as co-creators of knowledge and identifiers of societal problems. For example, in public deliberation forums citizens meet onsite or online to discuss policy questions that have scientific dimensions. While efficient in catalysing joint reflection, most deliberation forums are marked by their short-term impact on civic society (Jamieson, Volinsky, Weitz, & Kenski, 2017). Of more long-term impact are citizen science projects. They involve citizens as e.g. data providers on subjects that are selected by scientists or special-interest groups (Bonney et al., 2009). Some projects also encompass online or onsite discussion forums where scientists and citizens, or citizens themselves, can debate issues related to the problem at hand. Some of these forums are small-scale and regional, while others involve thousands, even millions, across geographical boundaries. Discussion forums that allow for dialogic communication are most likely to help sustain citizens' motivations and their capacity for action (Shirk et al., 2012).

Feedback mechanisms across citizen, scientific and policy fields differ markedly in processes where citizens handle policy-related problems and act on policy results. Dependent on the modes of citizen participation and distributed networks of governance (C. Peters & Witschge, 2015), citizens occupy different positions: from legitimating decisions not of their own making, to neglecting or revoking such decisions.

Finally, the communication of scientific evidence for policy is not generally a standard part of a scientific education. However, it is also a skill and a legitimate matter for training. Such training could refer to the scientific and other gains to be made from policy-related intervention as well as an improved understanding of the often-messy and fast-changing conditions of policy work. This is an area where personal and institutional knowledge development can be of great significance (on all sides). Given the large evidence base in this field, it is also very appropriate that this should be fed back into the training and developmental needs of scientific advisers. It is important to consider the practical implications of this at a European level.

Chapter 7: References

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Annex 1: Addressing the scoping questions

1. Complexity and uncertainty in science for policy

1.1 What principles, approaches and methods can be introduced into the European Commission science advisory processes to ensure their maximum relevance and usefulness for policymakers, whilst addressing complexity and uncertainty?

1.1.1 Addressing complexity

Section 2.3.1 deals with the issue of complexity. Complexity refers to the difficulty of identifying and quantifying causal links between a multitude of interdependent variables, under conditions of time dependencies and feedback loops (cf. Cairney, 2012; Underdal, 2010). Complexity requires therefore sensitivity to non-linear transitions, as well as to scale (on different levels). It also needs to take into account a multitude of cause-effect pathways and needs to consider the often difficult-to-draw distinction between effect and noise (Poli, 2013).

How does complexity affect the interaction between scientific experts and policymakers? The most important aspect is the emphasis on relationships between interconnected phenomena in dynamic interactions. Preiser et al. (2018) list six major characteristics of complex systems that are particularly relevant when dealing with policymaking. These are:

1. Principle 1: Complex adaptive social-ecological systems (CAS) are constituted relationally
2. Principle 2: CAS have adaptive capacities
3. Principle 3: Dynamic processes generate CAS behaviour
4. Principle 4: CAS are radically open
5. Principle 5: CAS are contextually determined
6. Principle 6: Novel qualities emerge through complex causality

These principles link the sub-questions raised by the European SAM (dissent among experts, different styles of reasoning, multiple frames and contexts). Complex systems relate to a variety of competing or sometimes compatible frames. There is no universal understanding of complex systems; rather they depend on the context in which they are observed and analysed, and they provide boundary conditions for interconnected elements within and between systems (Cilliers, 2002; De Martino et al., 2006). In the context of scientific advice, complex system theory suggests refraining from the separation of values and facts, since the facts only make sense in the light of specific values (Juarrero, 2002). Furthermore, when following a pragmatic orientation towards complex systems, Ansell and Geyer advocate a multidimensional, multifaceted and systemic approach to policymaking, supported by decision-making tools that are based on complex visualisations.

Dealing with complexity when interacting with policymakers, the report suggests the following lessons that can be learned from the literature:

- It is essential to involve the widest range of participants, covering the full range of relevant perspectives;
- It should start with a deliberative phase to explore different framings of the problem and agree on which framings (plural if needed) will be considered for analysis;
- Within each framing, it may be helpful to try to identify parts of the complex problem where specialist input could be useful and, as far as possible, frame the questions for those parts in a well-defined manner;
- Then in the analytical phase, different parts of the problem can be addressed by relevant specialists, using methods appropriate to each part. For those parts which can be framed as well-defined questions, it may be possible to express the impact of uncertainties using probability statements, for less well-defined questions only verbal expressions of uncertainty are available. However, in all cases the sources of uncertainty should be described (NUSAP is one of the options for this) and their impact on the answer should be characterised clearly and the evidence and reasoning for it should be explained.
- The analytic phase should feed back into the deliberative process, or be followed by a second round of deliberation, where the assessments or advice on the different parts of the problem are integrated by whatever process is appropriate (probably qualitative, given the complexity, ambiguity and values issues likely to be involved) and drawn to a conclusion.

Other aspects of complexity are covered under Section 5.7 (demonstrating what criteria should be used to design the interface between sciences and policymaking) and Section 4.3.2 (addressing biases by implementing an analytic-deliberative discourse).

1.1.2 Addressing uncertainty

Section 2.2 provides a major overview of the various dimensions of uncertainty and introduces different frameworks and taxonomies to break down the components of uncertainty. The US National Research Council's Committee on Improving Risk Analysis Approaches defined uncertainty as 'lack or incompleteness of information' (National Research Council, 2009). The report makes a clear distinction between uncertainty (incomplete information about the relationship between cases and effect) and ambiguity (experiencing scientific dissent or different interpretations of what is known) (Renn et al., 2011). The classification of uncertainty into technical, methodological and epistemological types was not supported by the Working Group. These three kinds of uncertainty are overlapping and do not match what is suggested in the literature. Section 2.2 provides three additional classification schemes and discusses their implications for policy advice. In addition, the handling of uncertainty associated with wicked problems is addressed in Sections 5.2 and 5.3.

1.1.3 How can different styles of reasoning be integrated?

The report addresses the plurality of disciplines, viewpoints and schools of thought in Section 3.4 and again in 5.1. However, the Working Group agreed that there is no recipe book for how to integrate these various approaches. Here, we approach the 'art of deliberation'. The combination of analysis (collecting and classifying evidence) and deliberation (making sense of this evidence) has been addressed in Section 4.3 as one of the means to address biases and heuristics. It has also been prominently anchored in the lessons learned in Chapter 6. Beyond this, there is little to add. A different issue is how to deal with wicked problems that require the consideration if different frames. Wicked problems are introduced in Chapter 2 and covered in much more detail in Sections 5.1 and 5.2. Here, the issue is plurality in frames. The report mentions several approaches of how to deal with the plurality of frames. Two are prominently introduced; Mode 2 knowledge production and knowledge quality assessment. They are examples of how to address this plurality. There are more concepts that deal with the same issue yet the common aspect of all these approaches is to identify different frames, analyse their assumptions and inner logic, determine commonalities and differences, and provide interpretations about what this plurality means for the topic under discussion.

1.2 What are the best practices in communicating uncertainty as part of the science advisory process?

This topic is addressed in Section 4.3. In accordance with Burns et al. (2003), science communication is defined as:

> *'The use of appropriate skills, media, activities, and dialogue to produce one or more of the following personal responses to science…: awareness, enjoyment, interest, opinion-forming, and understanding.'*

The literature on science communication is addressing the need for informing the general public or special audiences within the public. There is hardly any reference to the topic of scientific communication to policymakers. In the light of the debate on cognitive and technical biases, the Working Group felt that is was necessary to focus on the communication on complex and uncertain information to policymakers. The assumption has been that policymakers may not differ significantly from the rest of the population. In this line of argument, the report describes the main tasks and means of communicating complexity, uncertainty and ambiguity to a non-scientific audience, including policymakers.

Communicating information on uncertainty to non-technical audiences poses a number of challenges. Many studies have demonstrated that verbal expressions of uncertainty are interpreted in different ways by different people (Budescu et al., 2014; Theil, 2002). Variable interpretation of verbal terms can be reduced by presenting them together with numerical probabilities (Budescu et al., 2014) and reduced further still, though not removed, if the numerical probability is presented before the verbal expression rather than afterwards

(Jenkins et al., 2018). Studies on the communication of numerical ranges representing uncertainty have shown a small but non-negligible proportion of people focus on one end or other of the range (e.g. Dieckmann et al., 2015). The effectiveness of graphical formats such as box plots and histograms or probability density functions has been studied by various authors (e.g. J. A. Edwards et al., 2012; Ibrekk & Morgan, 1987). However, some of these formats are often used to represent variability rather than uncertainty, which may lead to misinterpretation. Similar problems may be expected with numerical probabilities, since these are also often used to express variability (e.g. frequencies or proportions) rather than uncertainty. For this reason, EFSA (2019) has proposed to present probabilities which quantify uncertainty as '% certainty' when communicating scientific assessments.

There is a body of literature that recommends communicating with frequencies rather than probabilities (e.g. Gigerenzer et al., 2007). However, Joslyn and Nichols (2009) point out that many of the studies in that literature required subjects to estimate probabilities in complex tasks involving base rates or the conjunction of more than one probabilistic event. They argue that this is a fundamentally different cognitive task from that required in a situation where a probability representing uncertainty of an event or outcome is provided to the audience, as would occur when using probability to express the likelihood of a scientific conclusion being correct. Joslyn and Nichols (2009) report an experiment in which uncertainty of forecast wind speed was provided to subjects in either frequency or probability format, and the latter was better understood. Further studies are needed to confirm whether this would occur in contexts other than weather forecasts.

Spiegelhalter (2017) reviewed a wide range of techniques used to communicate risk and uncertainty information. He reported that only tentative conclusions could be drawn, and offered tentative recommendations on general issues, the communication of numerical risks, and visualisations. Similarly, EFSA (2019) found that the available experimental evidence on the communication of uncertainty was limited and additional reasoning was needed to develop practical guidance. They concluded that further research would be needed to evaluate the performance of the approaches they recommend and to refine them in future, where needed.

As they were aware that these recommendations are not focused on policymakers, the Working Group felt that many of the insights that are empirically conformed to many different audiences could also apply to the situations where policymakers interact with scientists.

1.3 What are the main challenges in the EU's current policy and regulatory response to scientific complexity and uncertainty? How are Member States, international organisations and non-EU OECD countries responding to these challenges? How could a future EC science advisory system address them?

Addressed in the GCSA's Scientific Opinion (Scientific Advice Mechanism, 2019).

2. Appropriate and high-quality evidence for policy

2.1a What are the attributes of good science advice, both generally and specifically of science carried out for public policy? How well do the classic attributes of validity, reliability and relevance cover it?

The report is careful to avoid any over-generalisation about the quality criteria of good science in general. Given the broad scope of disciplines, including the humanities, there are only very few quality criteria that can claim validity for all scientific disciplines. Quality criteria such as reproducibility are extremely relevant for some sciences, but not for others. Most concepts of science also agree that science attempts to produce and test claims about reality. It includes descriptive (how reality is shaped), analytic (causal and functional relationships between phenomena) and — depending on the specific discipline — normative (how reality should be changed or altered) statements. The overall goal of arriving at a true account of reality remains the essence of scientific enquiry throughout all disciplines (similar attempts in N. R. Campbell, 1921, pp. 27-30). Using scientific expertise in science and technology studies is not identical, however, to generating scientific statements (Lindblom & Cohen, 1979, p. 7). In a policy arena, scientific experts are expected to use their skills and knowledge as a means of producing arguments and insights for identifying, selecting and evaluating different courses of collective action. Scientific knowledge is a source of evidence and advice that can play an important role in the formulation and development of policy- and decision-making, from short-term emergencies to long-term global challenges. In this context, good science communication promotes critique and self-correction, acknowledges the limits of data and methods, and faithfully accounts for the sources of evidence (Cairney, 2016; Kenny et al., 2017). To be used as a basis for advice, evidence has to include not only scientific insights, uncertainties and ambiguities, but also causal relationships and explanations, as well as other supporting factors. Scientific advice must then be based on the best available evidence and communicated in a transparent and accountable way, explicitly and honestly assessing and conveying uncertainties and tensions.

2.1b How well do the classic attributes of validity, reliability and relevance cover the good attributes of science?

The report does not pass judgement on the question because these three criteria are very valid and important if empirical sciences are involved or empirical studies are considered. As soon as interpretative sciences, based on hermeneutic methods, are included, these criteria are inappropriate. Therefore, the report concludes that the quality criteria of each discipline involved need to be taken into account if statements are made that belong or even touch upon the domain of such a discipline.

A requirement of this understanding of science is that knowledge claims are described in such a way that the procedures to accomplish the results can be independently reproduced and the results of scientific enquiries subjected to external review in order to assess their validity; peer review and reproducibility are the hallmarks of science to withstand tests in order to reduce the risk of inaccurate conclusions or, in some rare cases, fraudulent data (Fanelli, 2018). Science is often asked to provide impartial and reliable knowledge. However, scientific results are not always reliable, and advisers may be biased (Fanelli et al., 2017), searching for a particular outcome, e.g. as a result of being sponsored by a stakeholder within a policy domain (Bok, 2003; Greenberg, 2007). While there has been debate over the issue of reproducibility in science, there is also substantial evidence to suggest that talk of a 'crisis' in this respect is greatly exaggerated (Fanelli, 2018; O. H. Petersen, 2019).

An extended description of what science advice can offer to policymakers and how the quality can be judged can be found in Section 3.2.

2.2a What are the different kinds of scientific evidence that are relevant for advice to policy and under what conditions? What quality frameworks and methods can be applied to the evidence used for advice to EC policy, to ensure that the quality criteria are those most relevant to the different types of evidence needed?

Scientific expertise is used for supporting policymaking by providing the best available knowledge in understanding a specific problem, generating or creating policy options, evaluating the impacts of different decision options and providing meaning to discourse topics in society. Since such advice includes the prediction of the likely consequences of political actions in the future, experts are also in demand to give advice on how to cope with uncertain events and how to make prudent selections among policy options, in particular, if the policymaker faces uncertain outcomes and heterogeneous preferences (Cadiou, 2001, p. 27). Many policymakers expect scientific experts to help construct strategies that promise to prevent or mitigate negative and promote positive impacts of collective actions. In addition, scientific expertise is demanded as an important input to design and facilitate communication among the different stakeholders in debates, particularly about technology and risk (B. Fischhoff et al., 2011).

More insights about how the process between science advisers and policymakers should be designed and structured can be found in Section 5.7, where ten general principles are introduced and explained.

2.2b What quality frameworks and methods can be used to the plural evidence for policy to ensure that the quality criteria used are those most relevant to the different types of evidence needed?

The question may be misleading. Each discipline has developed methodological rules of how to delineate robust evidence. Due to complexity, uncertainty and ambiguity, even within a discipline, the outcomes of scientific enquiry may differ but there are limits to what can be labelled as scientific evidence. The boundaries of legitimate evidence are marked by the methodological rules that are taken for granted by the respective scientific community (see Section 3.4). Therefore, quality criteria depend on the disciplinary background in which advice is being articulated. However, most policy problems require inter- and transdisciplinary approaches. In these instances, in addition to making sure that disciplinary components obey the methodological rules of the respective discipline, they also have to meet additional criteria, which are all mentioned in Section 5.7. Another issue is how a scientific advisory body can assure that these rules are really adhered to and reinforced (compliance). In various institutional settings, peer review mechanisms are introduced. Other control formats include scientific enquiries, hearings or multiple science advisory groups with similar mandates (as a means of systematic comparisons).

2.3 What good practices (applicable to the EC context) exist for the use of expert knowledge and collective expert bodies, including for acknowledging the role of experts in the process of science advice?

This question is addressed in Section 5.9 of the report. It does not get wide coverage, however. The Working Group focused on how to ensure a high-quality process of giving advice to policymakers and did not focus on the institutional mechanisms that are need to install and control the quality of such a process. The reasons for not elaborating on institutional means was the plurality of national styles of policymaking and the role of expert advice therein and the existence of many functional equivalent institutional mechanisms to ensure a high-quality process.

2.4 What are effective ways of mitigating various types of biases in producing, selecting and interpreting evidence for policy?

The report includes a detailed section on cognitive, technical and issue-related biases, including interests and dependencies (Section 4.3). It lists the major cognitive fallacies that can be found in the literature and covers the overt political and special interest biases. However, it also alerts the reader that the term 'bias' may be misleading. Many of what has been called cognitive biases are heuristic strategies that are well suited to deal with many problems. Many psychological experiments on cognitive biases have been tested on abstract topics in laboratory settings, yet in real-life situations, many of these overt deviations from drawing rational inferences could not be observed (Jungermann, 1986).

In this sense, one should be cautious with the assumption that decision-makers lack the capacity to process complex scientific information in a rational manner. However, there are clear deviations from rules of logical reasoning that can also be found among decision-makers. There is no recipe book of how to avoid such biases. Most often, analysts believe that making policymakers aware of them can help them to avoid at least the most obvious fallacies (Parkhurst, 2017). Some more practical rules, such as reporting always relative and absolute frequencies when reporting about statistical evidence for cause-effect relationships, providing good illustration or simulations that provide a holistic image of the phenomenon and training decision-makers to deal with complex issues may be routes for overcoming some of the technical biases reported by Parkhurst and others (Kahneman, 2011).

In general, mitigation strategies to overcome biases are articulated for the individual level (e.g. Fruehwald, 2017), on the organisational level (e.g. Cristofaro, 2017), on the corporate level (e.g. Otuteye & Siddiquee, 2015) and, though less frequently, on the policymaking level (Bellé et al., 2018). The advice given focuses on cross-checking factual claims, being specifically cautious when decision options coincide with personal preferences, seeking external advice, avoiding group shifts and monitoring expected impacts once a decision has been reached. A lot of this is close to common sense and may not be very useful for designing mitigation rules for avoiding biases in the interactions between sciences and politics. The more social and ethical biases as pointed out by Parkhurst (2016) require institutional rules for assuring the integrity, independence and transparency of the advice mechanisms. These quality criteria for the governance of the consultation process are discussed in Section 5.7.

A conceptual approach for dealing with potential cognitive, technical and issue-related biases has been developed by the US National Research Council. The Council members addressed the issue of heuristics and biases by recommending a combination of analytic rigour, based on comprehensive peer review and methodological robustness and deliberative argumentation among a broad representation of stakeholders and policymakers (National Research Council, 2008; P. C. Stern & Fineberg, 1996). The concept of an analytical-deliberative process supports the creation of epistemic and political robustness (Lentsch & Weingart, 2009) and suggests a policymaking process based on the inclusion of experts, stakeholders and the general public (Hajer, 2003; Hajer & Wagenaar, 2003; National Research Council, 2008; Rauschmayer & Wittmer, 2006; Renn, 2008, p. 284; Sweeney, 2004; Webler et al., 2001). Sprain and Black (2018) have advocated a similar process that they labelled as 'deliberative enquiry'. The first element of analytical-deliberative processes refers to the inclusion of systematic and peer-reviewed knowledge. Systematic expertise is regarded as an essential resource for obtaining and utilising the background knowledge necessary to understand the complexity of wicked problems and policy issues and to anticipate the impacts of various policy options (de Bruijn & ten Heuvelhof, 1999; Horlick-Jones, Walls, et al., 2007; Klinke & Renn, 2014).

2.5 What are good practices in dealing with and communicating scientific dissent (i.e. legitimate and divergent interpretations of evidence) in the process of science advice, without opaque aggregation?

The report does not cover this issue in detail. It distinguishes between complexity, uncertainty, and ambiguity, thus providing explanations for the occurrence of dissent. Such dissent can arise from the multi-facets of complex systems, which lend themselves to different frames, and perspectives, from incomplete or uncertain knowledge providing different expressions for stating the degree of confidence into a specific finding or from ambiguity resulting in different interpretations of the evidence rather than the evidence itself (see Section 2.3.1.). The issue of how to deal with dissent is briefly mentioned in Section 4.4. Managing opposing views: The science advisers indicate any opposing scientific views and how deviating evaluations, assessments, interpretations or conclusions are justified there. In particular, they specify the assumptions that underlie different interpretations. There are also hints of how to cover this topic in Section 6.2. If the question is meant to address rules governing the handling of internal conflict within an advisory body, this aspect has not been covered in the document. However, normally it is handled similarly in most advisory bodies all over Europe: if a consensus is not found, a majority position and minority positions are published side-by-side and, as explained above, the reasons for the dissent are made transparent (Lentsch & Weingart, 2009).

3.1 What principles, practical experiences and lessons on science advice, as well as on the interaction between evidence, science advice and policy — are relevant and applicable to the EC context?

Addressed in the GCSA's Scientific Opinion (Scientific Advice Mechanism, 2019).

Annex 2: Background to the report

At their meeting early in 2018, the Group of Chief Scientific Advisors (GCSA) adopted a scoping paper (Group of Chief Scientific Advisors, 2018) that confirmed the Group's intention to produce a Scientific Opinion on *Making sense of science for policy under conditions of complexity and uncertainty*. The GCSA's resulting Scientific Opinion would be addressed primarily to policymakers who utilise scientific advice across the European Commission, and would also be of relevance to the governance of scientific advice in the Commission.

The overarching question being addressed is:

How to provide good science advice to EC policymakers, based on available evidence, under conditions of scientific complexity and uncertainty?

In June 2018, the GCSA chaired a scoping workshop at the European Commission. The objective of the workshop was to build on the initial scoping paper, by highlighting the areas of debate and sub-topics to address, as well as existing evidence requiring special attention in the drafting of the Scientific Opinion. An outcome of the workshop was a set of sub-questions, developed from the main question (European Commission Scientific Advice Mechanism, 2018).

Within the GCSA, Professor Pearl Dykstra led on this topic, in cooperation with other GCSA members, Professor Rolf-Dieter Heuer, Sir Paul Nurse and Professor Janusz Bujnicki.

The SAPEA Consortium was asked to conduct the evidence review on the topic. The SAPEA Board approved *Academia Europaea* as the Lead Academy, working with other SAPEA partners.

An overarching Coordination Group was established, chaired by Professor Dykstra. It was composed of members of the GCSA involved, Professor Ole Petersen (on behalf of SAPEA and *Academia Europaea*) and Professor Ortwin Renn (on behalf of the SAPEA Working Group). Staff members of the SAM Unit and SAPEA provided support.

SAPEA set up an international and interdisciplinary working group and appointed the Chair, Professor Ortwin Renn. Membership of the working group was based on a process of formal nomination by academies and assessed by a selection committee. The committee followed established SAPEA guidelines on ensuring fair representation on the working group in respect of gender, geographical spread etc., whilst adhering to the primary criterion of excellence in the field. All members of the working group were required to declare any conflict of interest.

The Working Group met three times in total, between September and December 2018. The Working Group oversaw the literature search, which was undertaken by information professionals at Cardiff University. Further sources were provided by members of the Working Group and SAM Unit.

The first draft of the report was submitted in early January 2019. The draft was critiqued by a group of invited experts at a workshop held on 11th February and resulted in a revised report. The second draft of the report went for peer review in March, leading to a third and final version. The final version of the report was endorsed by the SAPEA Board, on behalf of its member academies.

The GCSA's Scientific Opinion and the SAPEA Evidence Review Report are published simultaneously.

Annex 3: Literature search strategy statement

SAPEA, in collaboration with Cardiff University Library Services, created an online knowledge base to support the *Making sense of science for policy under conditions of complexity and uncertainty* project. This comprises the references cited within the Evidence Review Report (over 600 in total) and the results of literature searches.

Literature searches were conducted to address the questions posed within the SAM scoping workshop report (Group of Chief Scientific Advisors, 2018), as well as in response to specific requests made by members of the Working Group, who completed a template specifically designed for the task.

The search was undertaken using the LibrarySearch database. It combines results from print and electronic books and journal titles held within Cardiff University with a collection of full-text articles from Cardiff's electronic journal holdings, currently more than 73,000 titles. The results are provided by the Primo Central Index, an index of publishers and aggregator databases that connects with LibrarySearch to provide links to millions of journal articles and book chapters as well as conference proceedings, newspaper articles and scholarly Open Access content.

Filtering and selection of results was carried out by SAPEA staff at Cardiff University, based on relevance, and resulted in over 1,000 bibliographic records added to the knowledge base. The records were shared with the Working Group and were stored in an EndNote reference management database.

Search strategy	Number of references added to the knowledge base and shared with the Working Group
Advisory bodies/systems (in the context of policy(making) and Europe	25
Bias (in the context of science/evidence and decision(making) or policy(making))	75
Citizen science (in the context of policy(making))	86
Science/research communications (in the context of policy(making))	66
Complexity (in the context of science/evidence and policy(making))	51
Dissent (in the context of science/evidence and policy(making))	20
Ethics (in the context of evidence/science/research and policy(making))	90
The nature of evidence (in the context of science/research and policy(making))	26
Governance (in the context of science/research and policy(making))	60
Interdisciplinarity/transdisciplinarity/multidisciplinarity (in the context of policy(making))	30
Quality of science/research/evidence (in the context of policy(making))	45
Roles/functions (in the context of science/evidence and policy(making))	49
Science advice (general)	97
Science-policy interface/evidence-policy interface	65
Trust (in the context of policy(making))	50
Turns in science (linguistic, cultural, stochastic)	42
Uncertainty/complexity/ambiguity (in the context of science and policy(making))	100
Values (in the context of science and policy(making))	46
Ways of knowing (in the context of policy(making))	35
Total number of records added to the knowledge base	1058

Annex 4: Glossary of key definitions and terms

Advocacy	Arguing and/or acting in support of a particular cause, policy, belief, group of people, etc. (*A Dictionary of Public Health*, 2018).
Bacon, Francis	English philosopher (1561-1626), statesman and early advocate of the scientific method (*Oxford World Encyclopedia*, 2004).
Bayesian approach	A method of statistical inference, named after the English mathematician Thomas Bayes (1701-1761), that compares a hypothetical distribution (for example, the equal distribution of odds) with the observed distribution, even if this evidence is not conclusive. Based on expert judgement, one can derive a better and more adequate representation of the probabilities if one compares the *a priori* distribution with the *a posteriori* judgments of experts. This method allows one to combine prior information about a parameter with evidence from information contained in an expert sample to guide the statistical inference process (*Encyclopædia Britannica*, 2016).
Bounded rationality	A theory of rationality which recognises that instead of considering all alternatives, individuals must choose which alternatives to consider. They may spend considerable time searching for alternative courses of action and evaluating their consequences, but this is costly and usually falls short of complete knowledge. Accordingly, individuals bound their searches. Bounded rationality further postulates that the computational abilities and cognitive capacity of humans are limited, and that the assumption of maximisation may impose a heavy computational burden upon the decision-maker. Rather than predicting choice, bounded rationality is more concerned with the processes that persons use in making choices—that is, what kind of simplifying strategies and heuristic mechanisms they adopt (*Dictionary of the Social Sciences*, 2002).
Cartesian	Related to the writings or doctrines of the French philosopher René Descartes (1596–1650) (*A Dictionary of Psychology*, 2014).
Citizen science	(In the context of research) The collection and analysis of research data by members of the general public, typically as part of a collaborative project with professional scientists (*Oxford Dictionary of English*, 2010).(In the context of science for policy) Whilst citizen science can be defined in different ways (Bonney, Cooper, & Ballard, 2016), one form involves the 'engagement of non-scientists in true decision-making about policy issues that have technical or scientific components' (Lewenstein, 2004).

Complexity theory/ complex systems	The scientific study of complex systems. Complexity theory originates in the ideas of complex adaptive systems in the natural sciences and nonlinear dynamics in mathematics, and provides a theoretical and methodological framework for understanding social systems which share characteristics of complex phenomena and relationships such as self-organisation, emergence, nested structures, and far-from-equilibrium states. Complexity theory shares with chaos theory a focus on the sensitivity of outcomes to initial conditions and where outcomes cannot be explained simply in terms of interactions between the individual parts. Social network analysis, dynamic modelling and agent-based modelling are examples of methods used under complexity theory (*A Dictionary of Social Research Methods*, 2016).A system is complex when there are strong interactions among its elements, so that current events heavily influence the probabilities of many kinds of later events (Axelrod & Cohen, 2000).
Confidence interval	A measure of the margin of error in the estimation of a population parameter, on the basis of a random sample of that population. Confidence intervals are assigned a confidence level which theoretically could lie anywhere between 0 and 100 per cent but typical values are 95 per cent and 99 per cent. So, a 95 per cent confidence interval indicates that if an infinite number of samples were drawn, 95 per cent of the resulting frequency counts would be located within the confidence interval (*A Dictionary of Social Research Methods*, 2016).
Construal level theory	A theory which proposes that psychological distance from (or proximity to) objects and events is associated with different mental models (*The Oxford Encyclopedia of Climate Change Communication*, 2017).
Decision tree	A graphic image showing decisions and events leading to option-specific outcomes, with probabilities and outcomes reflected in a branching of the image (*A Dictionary of Social Research Methods*, 2016).
Deliberative theory	The motivational aim of deliberative theory is to legitimise political decisions by creating procedures that allow democratic decisions to be a result of mutual understanding, publicly expressed reason, and broadened political inclusion (*Concise Oxford Dictionary of Politics and International Relations* 2018).
Delphi method	A method for structuring a group communication process in several iterative steps of assessment and re-assessment so that the process is effective in allowing a group of individuals, as a whole, to deal with a complex problem (Linstone & Turoff, 1975).
Dialogic	Something that involves two-way interaction (*A Dictionary of Human Geography*, 2013).
Empirical/empirical sciences	Based on, concerned with, or verifiable by observation or experience rather than theory or pure logic (*Oxford Dictionary of English*, 2010).
Epistemology/ epistemic	The philosophy of the theory of knowledge, especially with regard to its methods, validity, and scope, and the distinction between justified belief and opinion (*Oxford Dictionary of English*, 2010).

Fake news	News that is not true. The growth of social media has meant that fake news can propagate very quickly from a variety of media sources to the point where many users of the Internet believe it (*A Dictionary of the Internet*, 2013).
Falsification	An approach to testing the validity of any hypothesis or conjecture that entails the search for evidence or reasons that might entail its rejection or modification. The approach was advocated by philosopher of science Karl Popper in the 1930s in relation to science and empirical (or factual) knowledge. Popper contrasted falsification with verification, which involves the search for evidence that confirms a hypothesis or conjecture. Popper argued that falsification is more rigorous because just one piece of negative evidence can challenge 99 confirmatory pieces (*A Dictionary of Human Geography*, 2013).
Framing	The framing of a problem or an issue describes how evidence is selected and presented, how it is embedded in a larger context of political programmes, values or interests, and how it forms a plausible narrative (Entman, 1993).
Fuzzy set	A generalised concept of a set in which elements have continuously graded degrees of set membership ranging from 0 to 1, rather than either not belonging (0) or belonging (1) as in conventional set theory (*A Dictionary of Psychology*, 2014).
Greenwashing	A term (combining 'green' and 'whitewash') that is used to describe the activity (for example, by corporate lobby groups) of giving a positive public image to practices that are environmentally unsound (*A Dictionary of Environment and Conservation*, 2016).
Heuristics	An approach to problem-solving or understanding that is based on a methodological shortcut that will lead not to a perfectly rational outcome, but to a workable one. Heuristics enables someone to reach quicker decisions and reduce the cognitive load involved in decision-making. Heuristic approaches are developed from previous experience and can work well in many situations. They can also lead to problematic bias. Heuristics includes availability (focusing on what easily comes to mind), representativeness (a distortion of probability that assumes that because something is more representative it is also more likely), and familiarity (assuming past behaviour will work in the current context) (Tversky & Kahneman, 1974).
Interdisciplinary	Applying the knowledge and skills from different academic disciplines or subjects that are normally regarded as distinct (*A Dictionary of Environment and Conservation*, 2016).
Interpretative (as a method)	Methods of analysis that rely on the interpretive skills of the researcher to turn the data into meaning. Typically, interpretive approaches are applied to qualitative data (*A Dictionary of Human Geography*, 2013). *See also: Qualitative.*
Laplacian	Referring to Laplace, Marquis Pierre Simon de (1749–1827), French mathematician, astronomer, and physicist (*The New Oxford Dictionary for Scientific Writers and Editors*, 2009).

Meta-analysis (as a method)	The quantitative/statistical techniques for integrating/combining the findings obtained from many individual studies to arrive at a robust judgement about the causal connection between a trigger and an effect (or outcome of interest) (*A Dictionary of Social Research Methods*, 2016).
Methodology	A system of methods used in a particular area of study or activity (*Oxford Dictionary of English*, 2010).
Mode 1 and Mode 2 knowledge	'Mode 2 knowledge' is typically problem-driven and multidisciplinary, with the external environment (rather than academic disciplines) setting the agenda for research. In contrast, 'mode 1 knowledge' emerges from 'classical' scientific enquiry since it is shaped by discipline-specific academic groups pursuing rigorous causal or functional analysis within a domain of the respective discipline (*A Dictionary of Human Geography*, 2013).
Monte Carlo simulation	Monte Carlo Simulation is a statistical technique for stochastic model calculations and analysis of error propagation in (model) calculations. Its purpose is to trace out the structure of the distributions of model output. In its simplest form, this distribution is mapped by calculating the deterministic results (realisations) for a large number of random draws from the individual distribution functions of input data and parameters of the model. To reduce the required number of model runs needed to get sufficient information about the distribution in the outcome (mainly to save computation time), advanced sampling methods have been designed such as Latin Hyper Cube sampling. The latter makes use of stratification in the sampling of individual parameters and pre-existing information about correlations between input variables (Saltelli et al., 2008).
Multidisciplinary	The coordinated application of several academic disciplines or subjects without attempting to develop a common understanding of the phenomenon to be studied *(A Dictionary of Environment and Conservation, 2016). See also: Interdisciplinary, Transdisciplinary.*
Normal science	According to an influential idea first presented by the US historian and philosopher of science Thomas Samuel Kuhn (1922–96) in his book *The Structure of Scientific Revolutions* (1962), a period in the development of any scientific discipline in which there is general acceptance and agreement as to the basic concepts, and further pathways to improve knowledge (*A Dictionary of Psychology*, 2014). *See also: Post-normal science.*
Normative	Hypotheses or other statements about what is right and wrong, desirable or undesirable, just or unjust in society. (*A Dictionary of Sociology*, 2009). More specifically, describing any academic argument that criticises current arrangements and calls for the creation of a better future (*A Dictionary of Geography*, 2009).
NUSAP	NUSAP (Numeral, Unit, Spread, Assessment, Pedigree) is a notational system and tool which aims to provide an analysis and diagnosis of uncertainty in science for policy. The NUSAP system structures the systematic appraisal and communication of uncertainty and knowledge quality (van der Sluijs, 2017).

Qualitative	Concerned with meaning associated with observed behaviour, rather than with numerical measurement. The emphasis is on subjective understanding, communication, and empathy, rather than prediction and statistically valid explanations (*A Dictionary of Geography*, 2009).
Peer review	A procedure where scholarly work is evaluated by experts of the same discipline against a set of criteria to ensure that it meets the quality standards necessary for publication. Peer review is widely accepted as the best method for research validation and ensuring quality publications. The peer-review process may be open, where both author and reviewer are known to each other, or it may be a blind process where the reviewer or the author is anonymised or both author name and reviewer name are hidden (*A Dictionary of Publishing*, 2019).
Populism	A political discourse suggesting that the interests of the mass of the people are opposed to the interests of an elite; leaders of populist movements claim to be cognisant of the true interests of a larger entity such as class, nation or race (*A Dictionary of Human Geography*, 2013; McIntyre, 2018).
Post-normal science	A form of science, and research more generally, that must cope with evidential uncertainty, disputed or even conflicting values, high stakes, and the urgent need for action. 'Normal science' denotes a scientific practice where investigators' findings are well-evidenced and, in value terms, relatively uncontroversial, often leading to practically effective interventions or policies. By contrast, the topics of interest to post-normal science are ones where there are real doubts about what current evidence signifies, where the implications of science's discoveries are significant, where pre-emptive action to avert major ecological or social problems may be required now, but where large disagreements arise over whether and how such action should occur (*A Dictionary of Human Geography*, 2013). *See also: Normal science.*
Post-truth	Relating to or denoting circumstances in which objective facts (even if they are well known) are less influential in shaping public opinion than appeals to emotion, common sense and personal belief (*Oxford Dictionary of English*, 2010).
Postulation	A proposition that is proposed as true without further demonstration, either because it is judged not to require proof or because it is assumed for the sake of discussion (*Oxford Dictionary of English*, 2010).
Precautionary principle	The precautionary principle is a legal principle for the governance of risks that asks that precautionary measures should be taken to reduce potential risks in cases where scientific evidence of risk is insufficient, inconclusive or uncertain and there are indications through preliminary objective scientific evaluation that there are reasonable grounds for concern that the potentially dangerous effects on the environment, human, animal or plant health may be inconsistent with a chosen level of protection (European Commission, 2000).

Probability distribution	A description of the possible values of a random variable, and of the probabilities of occurrence of these values (*A Dictionary of Statistics*, 2014).
Pseudo-science	A collection of beliefs or practices mistakenly regarded as being based on scientific method (*Oxford Dictionary of English*, 2010).
Randomised control trials	Experimental methods applied to the study of the effectiveness of treatments, especially treatments not administered in a clinical or laboratory setting, such as educational or economic interventions. They are considered as a rigorous way to identify cause-effect relationships between treatment and outcome and to assess the cost-effectiveness of a treatment (*A Dictionary of Social Research Methods*, 2016).
Reproducibility (replicability)	The extent to which measurements made under one set of conditions (or by one observer) can be repeated under different conditions (or by another observer) (*A Dictionary of Statistics*, 2014).
Rule of thumb	A rule for general guidance, based on experience or practice rather than theory or systematic enquiry (*The Canadian Oxford Dictionary*, 2004).
Science communication	The practice of communicating science-related topics to non-experts. The communication of science takes many forms, from written articles in newspapers, magazines and blogs to standing in front of a non-expert audience to give a lecture or leading an interactive science workshop. Science communication often includes public engagement, aiming to involve the general public in two-way scientific conversations, usually about shared issues, common understanding of phenomena and joint searches for the solution of problems (BIG STEM Communicators Network, 2019).
Scientism	The belief that scientific methods can be applied to all problems, with the consequent application of inappropriate scientific methods in unsuitable circumstances (*A Dictionary of Public Health*, 2018).
Stochastic	Having a random probability distribution or pattern that may be analysed statistically but may not be predicted precisely for each case (*Oxford Dictionary of English*, 2010).
Systematic review (as a method)	A review of research using methodical and organised procedures for identifying, selecting, appraising, and synthesising the primary findings of a large number of research studies. It is especially suited to reviews whose principal aim is to assemble, pool, and summarise research data relevant to a clearly specified question or set of questions (*A Dictionary of Psychology*, 2014). *See also: Meta-analysis.*
Tacit knowledge	The informal understandings of individuals which they have not verbalised and of which they may not even be aware, but which they may be inferred to know (notably from their behaviour). This includes what they need to know or assume in order to produce and make sense of messages (social knowledge and representational knowledge). Tacit knowledge is distinguished from explicit or formal knowledge and the term is sometimes used synonymously with common sense, in the sense of taken-for-granted knowledge (*A Dictionary of Media and Communication*, 2011).

Transdisciplinary	The concept of transdisciplinarity combines three main aspects. First, it addresses research practices that address issues beyond the boundaries of each discipline, adapt research subjects, methods and approaches to non-scientific problems and develop solutions for socially complex problems independently of disciplines. Secondly, transdisciplinary research is based on an intensive exchange between knowledge producers and knowledge recipients across all phases of the research process. Thirdly, the transdisciplinary approach is characterised by an explicit integration of knowledge carriers outside of science. For complex questions in particular, experience knowledge and often also contextual knowledge in society are relevant in order to develop not only theoretically conclusive but also practical solutions (Renn, 2019). *See also: Interdisciplinary, Multidisciplinary.*
Trans-science	A term coined by physicist Alvin Weinberg, referring to the uses of science in issues which arise in the course of the interaction between science or technology and society that hang on the answers to questions which can be asked of science but which cannot be answered by science. He gave the example that determining at the 95% confidence level by a direct experiment whether 150 millirems of ionizing radiation will increase the mutation rate in mice by 0.5%, would require repeating the experiment on 8,000,000,000 mice. That number is so staggeringly large that, as a practical matter, the question is unanswerable by direct scientific investigation (Weinberg, 1972).
Typology	A system of groupings that aids understanding of the things being studied by distinguishing certain attributes or qualities among them that serve to link them together into a closed set of items (*Oxford World Encyclopedia*, 2004).
Values	Important and lasting beliefs or ideals shared by individuals, groups or cultures about what is good or bad and desirable or undesirable. Values have major influence on a person's behaviour and attitude and serve as broad guidelines in all situations. Some common values are fairness, freedom, environmental quality or human welfare (*Business Dictionary*, 2019).
Whitewashing	A deliberately attempt to conceal unpleasant or incriminating facts (about a person or organisation) (*Oxford Dictionary of English*, 2010). *See also: Greenwashing.*
Wicked problem	A problem that lacks simple or straightforward responses, has many interdependencies, and is socially complex, and attempts to address such an issue often lead to unforeseen consequences (*The Oxford Encyclopedia of Climate Change Communication*, 2017).

Annex 5: List of abbreviations

Abbreviation	Meaning
ALLEA	All European Academies
ANSA	European Union Agency Network for Scientific Advice
BfR	German Federal Institute for Risk Assessment
BSE	Bovine spongiform encephalopathy (cow disease)
CAS	Complex Adaptive Social-ecological systems
CCA	Canadian Council of Academies
COST	European Cooperation in Science and Technology
CPVO	Community Plant Variety Office
EASA	European Aviation Safety Agency
EASAC	European Academies' Science Advisory Council
EC	European Commission
EEA	European Environment Agency
EFSA	European Food Security Authority
EGE	European Group on Ethics in Science and New Technologies
EMEA	European Medicines Agency
EU	European Union
GESAMP	Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection
GIGO	'Garbage in — garbage out' rule
GNP	Gross National Product
IAP2	International Association for Public Participation
INGSA	International Network for Government Science Advice
IPBES	Intergovernmental Platform on Biodiversity and Ecosystem Services
IPCC	Intergovernmental Panel on Climate Change
IRGC	International Risk Governance Council
JRC	Joint Research Centre
KQA	Knowledge Quality Assessment
NAS	National Academy of Science
NUSAP	Numeral, Unit, Spread, Assessment, and Pedigree (system for uncertainty assessment)

OECD	Organisation for Economic Co-operation and Development
OHIM	Office of Harmonisation in the Internal Market
PNS	Post-normal science
POST	Parliamentary Office of Science and Technology
PR	Public Relations
PRA	Probabilistic Risk Assessment
RCEP	UK Royal Commission on Environmental Pollution
SAC	Scientific Advisory Committee
SAPEA	Science Advice for Policy by European Academies
SCHEER	EU Scientific Committee on Health, Environmental and Emerging Risks
SRU	German Advisory Council on the Environment
STAP	Scientific and Technical Advisory Panel
STS	Science and Technology Studies
TTC	Threshold of Toxicological Concern
UNSCEAR	United Nations Scientific Committee on the Effects of Atomic Radiation
(US-)NRC	US National Research Council
WBGU	German Advisory Council on Global Change
WHO	World Health Organization
WQA	Water Quality Association

Annex 6: List of figures and tables

Annex 7: Working Group Members

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