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Assessing emerging technologies—Methodological challenges and the case of nanotechnologies

Torsten Fleischer *, Michael Decker, Ulrich Fiedeler

Institute for Technology Assessment and Systems Analysis (ITAS), Forschungszentrum Karlsruhe GmbH, P.O.B. 36 40, D-76021 Karlsruhe, Germany

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Abstract

Technology Assessment reflecting on R&D and technological trends in the area of nanotechnology and its implications is confronted with the problem that most scientific endeavours of nanotechnology can be allocated to basic research while most of the technological visions related to nanotechnology are far (>10 years) in the future. Since *technology* assessment has to integrate the socio-economic context of a technical product in order to be comprehensive, in the case of nanotechnology a preparing step is necessary which connects the ongoing basic research with the visions communicated either by the scientist themselves or by the media. In this paper we propose to adapt the well known tool 'roadmapping' to contribute to the solution of this problem. This poses new challenges for roadmapping methodology in terms of level of aggregation and timeframe.

Keywords: Science and technology roadmapping; Technology assessment; Nanotechnology

1. Introduction

Emerging technologies pose considerable challenges for 'classical' technology assessment (TA). If TA focuses on the outcomes or impacts of a technology, it can be performed only at later stages of technology development—when societal implications can easily be identified and determined. On the

* Corresponding author. Tel.: +49 7247 824571; fax: +49 7247 824806.
E-mail address: Torsten.Fleischer@itas.fzk.de (T. Fleischer).

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other hand, decision support and policy making require information on the potential consequences of the introduction of new technologies before they are widely implemented, i.e. at early stages of their development when the direction of the innovation process already can be influenced but its implications can hardly be foreseen.

The assessment of emerging technologies implies the introduction of new methods into the toolkit of the TA practitioner. These methods are coming from 'neighbouring' disciplines and normally were developed for other purposes. Their potential for implementation and the needs for modification have to be discussed and tested.

2. Assessment of emerging technologies—changing framework and new questions

Technology Assessment (TA) is a scientific, interactive and communicative process with the aim to contribute to the public and political opinion forming on science and technology related societal aspects [1] like exploitation of potential, dealing with secondary effects, and technological risks, overcoming problems of legitimacy and technology conflicts. It produces knowledge, orientation and procedures to deal with societal challenges in coping with technology.

Over the last years, the landscape for Technology Assessment has significantly changed. TA has started with the investigation of large complex technologies (conventional or nuclear energy technologies, aerospace technologies, . . .)–which were developed and deployed with significant participation of national governments–for 'customers' in politics like parliaments or administrations.

During the last years, the technological focus has somewhat shifted towards rather small, widely distributed (some would say decentralised) technologies where the impacts arise rather from a single component itself but from the large number of components and their widespread application, from the new type of complexity and interdependence that these components form when they are interacting, and from the change in economic and societal patterns initiated by the almost ubiquitous usage of these technologies.

Some technologies to be investigated are so-called 'enabling technologies'. They are–often crucial–technological prerequisites for other technologies, products and processes which are expected to impact existing technologies by expanding their usefulness, to enable new technological approaches and to trigger wider applications in a number of industries. Enabling technologies often have no direct–easily recognisable–connection with applications which makes it difficult to even determine relevant impact categories. Therefore it is necessary to perform intermediate analysis steps to connect these technologies to applications or visions for their integration in application technologies or products.

Together with the new kinds of technologies to be assessed, the role of governments or politics as important players in the innovation process has changed. First, there is a significant shift away from a direct governmental participation in the innovation process towards a concentration of national governments on the shaping of framework conditions for innovation. This is due to many reasons: Globalisation has altered the roles and influence of national policies and industries, political paradigms have changed, EU legislation and international competition leave less room for direct governmental activities in many technological fields.

In the last years, in many countries–due to economic and social pressures–there is a shift of focus towards technologies that stimulate or support economic growth, sometimes corresponding with the requirement to develop technologies that contribute to sustainable development (whatever the criteria for that might be).

Most funding organisations or contract awarders require valid, scientifically sound, knowledge-based, often quantitative, information on future developments of technology and its interaction with society before they are widely implemented, i.e. at early stages of their development when the direction of the innovation process already can be influenced. But most questions about the relevant consequences and options to influence it arise in the later phases of the innovation process, from the diffusion to the market, the use of technology and its disposal. This holds considerable methodological challenges with respect to analysis and assessment for all emerging technologies, but especially for emerging enabling technologies.

The principle of taking into account the knowledge about presumed or probable technology impacts in decisions already at an early stage is part of the basic concept of technology assessment. It was introduced, in its very beginning, as an early warning of technological risks and unintended consequences, later also as a tool for an early diagnosis of the chances and potential of technology.

It is perhaps not ill-founded to state that the treatment of central challenges of the sustainability discussion, particularly the sustainability assessments of technology, is prepared by decades of experiences with technology assessments. Consideration of the long term perspective, the dealing with the integration problem, complex cause/effect-relations and the inclusion of extra-scientific communication already have been practised for a long time. One can therefore go back to conceptions and methodical approaches of technology assessment for sustainability assessments of technology [2].

The requirements on sustainability assessments and their consideration in decision-making represent until now unknown degree of methodical challenges even with regard to very ambitious concepts of technology assessment, because impact identification and assessment have to be carried out at an extremely early stage and their results are expected to find consideration in practical decisions. It is no exaggeration to say that the known methodological problems of technology assessment come to a head here.

3. Nanotechnology

Nanotechnology is among the most prominent emerging technologies, they are heralded as a key technology for the 21st century. These–potential–innovations offer numerous benefits. There are great expectations among policymakers, scientists and industry representatives that nanotechnology may–or will–contribute to economic prosperity and sustainable development (for an up-to-date and comprehensive overview see Ref. [3]). On the other hand, nanotechnology has been the subject of an extensive public debate in Europe and the United States. Especially the risks of nanotechnology–from the suspected asbestos-like properties of some nanoscopic materials and the resulting dangers for human health to the potential thread by self-replicating nanobots turning the entire world into ‘grey goo’–got broad media coverage and public awareness. Obviously, nanotechnology is a case for technology assessment.

Technology Assessment of nanotechnology has to deal with several methodological challenges: First of all: Up to now it is quite blurred what in detail should be considered as ‘nanotechnology’—and what not. Until now, there is no definition of nanotechnology that is generally accepted in the scientific community. Perhaps such a definition is impossible at all. The ‘definitions’ proposed–and used (?)–by research policy or its think tanks and consultants are rather broad and unspecific, and they leave lots of room for interpretation. There were several attempts to transfer these descriptions into an operational definition, the most elaborate and stringent one is that developed by an expert working group coordinated by the Europäische Akademie zur Erforschung von Folgen wissenschaftlich-technischer Entwicklungen Bad Neuenahr-Ahrweiler (European Academy for the study of the consequences of scientific and technological advance) [4]: *Nanotechnology is dealing with functional systems based on the use of sub-units with specific size-dependent properties of the individual sub-units or of a system of those.... Functional systems are systems where the (technological or natural) functionality to be considered provides the criteria for defining system boundaries.... The specific-size dependence of these properties becomes evident when they a) no longer follow classical physical laws but rather are described by quantum-mechanical ones; b) are dominated by particular interface effects; c) exhibit properties due to a limited number of constituents, since the usual term* 'material' *refers to an almost infinite number of constituents (e.g. atoms, molecules) displaying an averaged statistical behaviour.*

Surprisingly, this definition does not refer to a particular part of the length scale where nanotechnology usually is expected to be 'at home'. Common 'definitions' traditionally limit nanotechnology to structures with a size somewhere between 0.1 and 100 nm in at least one dimension. The authors of the above definition consider this interval 'as a good approximation', but not as a 'plausible measure to define Nanotechnology' because one can find structures within this interval that do not show these 'specific size-dependent properties' which on the other hand can occur also in structures with sizes above 100 nm (or even 1000 nm). They propose that the name-giving order of magnitude of nanotechnology should not be mentioned in the definition, because this would imply exclusion rules independent from a scientific evaluation of the fundamental working principles of a functional system described by the three criteria.

According to this definition (but also interpreting other widely used descriptions of the field), nanotechnology is neither a specific technology nor is it a definite group of technologies. Nanotechnology comprises a wide range of approaches that are quite heterogeneous with regard to their subjects of investigation, possible applications and imaginable periods of realisation. Many of the developments called 'nanotechnology' are scientific findings and curiosities rather than R&D results close to a technological application. Very often, even the engineering and economic feasibility has not yet been clarified.

What does that mean for the technology assessment of nanotechnology? The first part of the answer is rather simple: For a valid and sound assessment, the monolith 'nanotechnology' has to be blasted into sensible and workable pieces. This is necessary not only for the analytical part of a TA, but also for the communication of assumptions and results during or at the end of a TA process since the current situation creates a lot of terminological fuzz, misinterpretations and misconceptions. Many discussions about nanotechnology tend towards a problematic generalisation. When scientists, politicians, journalists or 'people in the streets' are discussing nanotechnology, they all have their own ideas and assumptions, interpretations and examples, scientific approaches and experiences in the back of their head. These are usually not made explicit, but they shape the content and the structure of their arguments when they talk or write about nanotechnology 'as a whole'—and very often avoid or prevent a constructive discussion.

The second part is more complicated: Most activities that are considered as R&D in the field of nanotechnology are basic or applied research rather than technology development. For most results and findings it is rather vague for which application they could be used. Very often, it is still unknown, if and how they can be developed further into usable components or systems and integrated into reliable and marketable products.

The segment of 'nanotechnology' that is closest to a widespread application is the field of 'nanomaterials'. Nanomaterials are an essential part of the overall field of nanotechnology. They can be considered as the most important bridge between basic research and marketable products and processes. As so-called, 'enabling technologies', they are technological prerequisites for numerous innovations in many technological fields–from comparatively simple technologies for every day use (like cosmetics or pigments in paints), energy technologies or information and communication up to biotechnologies–without their interdependence being always obvious at first glance. Some nanomaterials-based products and processes are already on the marketplace, many more will very likely be seen in the near or mid-term future.

Nanomaterials show great economic potential, e.g. by substituting other materials or by making available new functionalities and thus enabling new products and creating new markets. It is also expected that nanomaterials may contribute to the reduction of the ecological footprint of classical production processes by reducing energy and material consumption.

For nanomaterials, two layers of assessment exist. The first one is the assessment of the impacts of its production. Although there are many knowledge gaps and uncertainties–e.g. about the up-scaling of the current processes used for material production and structuring to an industrial production level or about the health and environmental hazards that actually can arise from nanomaterials –, the general methodology can be adapted from procedures that are broadly used in the assessment of conventional materials technologies. Methods like Life Cycle Analysis or Materials Flow Analysis are comparatively sharp swords in the analysis and assessment of ecological and economic impacts of new materials technologies. These established methods are common in technology assessment and widely accepted internationally [5].

But the hopes and questions reach much further. Rather than the nanomaterials themselves, their use in new products and processes and their application in existing or new contexts, and the structural changes in technology, economy and society possibly initiated by them will have considerable consequences.

Since many nanotechnology-related developments are still in an early phase, at present and in the future researchers, developers and users are faced with strategic decisions on the continuation of their efforts again and again. In this situation, is it possible to find ways to consider knowledge about the potential impacts of a technology–which admittedly is gained with high uncertainty–and its assessment with regard to sustainability already in early phases of technology development? Are there approaches to let it become part of decisions which are already taken at early stages of an R&D project–about its objectives, its design or its course–in order to identify and to strengthen positive sustainability effects, the "sustainability potential" of technologies, and to recognise, to mitigate or to even avoid negative impacts on sustainability?

Wanting to do this completely ex ante certainly means to overstrain the ambitions of this intention. The aim rather is to initiate a process of shaping of technology in which the emergence of new technologies is accompanied by mutual co-operation between technology development and impact analysis, between sustainability research and nanosciences, and perhaps also between market research and technology assessment. Such a reflexive procedure surely would take into account the numerous demands from the debate on sustainable research and technology policies.

4. Roadmapping methodology as a tool for technology assessment of nanotechnology?

4.1. Science and technology roadmapping—a brief introduction

A standard definition of roadmap or 'roadmapping' does not exist. There is considerable diversity among practitioners as to what constitutes a roadmap and the roadmapping techniques employed [6].

The term 'roadmap' is widely used, starting from graphical representations of technology development paths and their application environments up to detailed and ambitious descriptions of future technology requirements and research needs. (Even in politics the term is used for implementation plans of political goals.) For a detailed discussion of the different types of roadmaps, their scopes, objectives, methodologies and time-scales see e.g. Refs. [6–8].

Among the different types of roadmaps, technology roadmaps are those with the longest history. Companies have started to develop and apply technology roadmapping in the mid-1980s. It has become a widely used technique during the past two decades from the perspective of both individual companies and entire industries. To our knowledge, the term 'science roadmap' has been proposed first by Robert Galvin in a 1998 article in Science [9]. Kostoff and Schaller–without any explicit justification–'re-integrated' both types. According to them, a "S and T (science and technology, T.F.) roadmap provides a consensus view or vision of the future S and T landscape available to decision makers. The roadmapping process provides a way to identify, evaluate and select strategic alternatives that can be used to achieve a desired S and T objective." [6] The probably most comprehensive overview of relevant research on and current knowledge about roadmapping, together with a critical discussion of the potential of roadmapping approaches–which are usually applied to sustaining technologies–to offer insights into disruptive technologies, can be found in a recent double issue of the journal 'Technological Forecasting and Social Change' [8].

Generally speaking, we consider 'roadmap' as an umbrella term for a group of techniques that support the structurization of complex interdependent processes and are intended to serve as decision aids for strategy building and planning in organisations that depend on and participate in the development of science and/or technology.

4.2. Roadmapping as a precursor of a TA process for specific nanotechnology applications

The situation described above–rather broad and largely unstructured field of investigation, mostly enabling technologies at early stages of development, emerging public debates about chances and risks and calls for technology assessment of these technologies, political requirements to orientate R&D budgets on the potential contribution of new developments to sustainable development–puts some pressure on the TA practitioner. There is a growing need to connect current nanotechnology research activities with visions of applications as well as to structure this field of investigation.

Similar to roadmapping, there is no general methodology for technology assessment. TA projects can differ by task, subjects and questions of investigation and addressee. Their design, structure and methodology depend on these factors and have to be determined on a case-by-case basis, taking the contextual framework into account [10]. There are, however, myriad proposals for a basic structure of a TA process with the oldest ones dating back to the early Seventies. Most of them contain–with either several overlaps or distinctions and often using varying terminology–the following basic elements (1) definition of task and system (2) analysis of technology, their applications and framework (3) impact assessment (4) evaluation and development of options.

Many activities that are considered as nanotechnology are closer to R&D for enabling technologies than they are embedded in a product (or process) development, and they are very often in a rather immature state. To either integrate these activities into a TA process or make them accessible for TA questions, a preceding step has to be performed. Its central goal is to obtain a well-structured connection between R&D activities in this field and potential fields of application and ideas for products. This has to be as specific and reliable as necessary to be the basis for a valid and sound technology assessment and should include not only the perspectives and knowledge of the developers and proponents of a technology, but also the views of implementers, users and potential customers.

For that purpose it is proposed to fall back upon experiences with successful roadmapping exercises and to adapt the general concept of science and technology roadmapping to include it–as a precursor–into the TA process for selected applications of nanotechnology. This should not be confused with other–ongoing or finished–roadmapping activities in or around the field of 'nanotechnology' [see e.g. 11–14]. These roadmaps are intended to serve other purposes and follow more or less classical trajectories of roadmap development and application which cannot be discussed here in any more detail. In short, the methodical challenge for our program is to develop roadmaps that combine the disaggregation level of a product roadmap with the timeframe and the inherent uncertainties of strategic roadmaps for branches or industries.

Essential part of many roadmapping concepts is an organised and moderated process with a multi-disciplinary and cross-functional group of experts to develop and visualize an analytical structure (or architecture) that shows how the different technological elements fit together, interact, depend on each other or are constrained by technical (or occasionally socio-economic) factors. Especially this exercise is expected to deliver more knowledgeable and thus reliable perspectives about the interdependences between scientific and technological developments, internal and external challenges and products or applications than many other approaches. This information is necessary not only for the analytical step, it may offer valuable insights for the entire TA process. Other assumed benefits for the TA practitioner are the identification of gaps of knowledge, qualified estimates about technological hurdles and the degree of difficulty to overcome them and related time horizons, or the provision of options for alternative solutions or even new concepts.

By serving as kind of an expert-based participatory approach to the systems analysis step of a TA, it is expected that this process allows more reliable judgements about product ideas and visionary applications thought up by proponents (and sometimes propagandists) of nanotechnology, about the realism and the realisation periods of these concepts as well as about the potential of competing conventional technologies. The possibility to bring in arguments and perspectives from people who are usually not involved in the technological development process at an early stage may be an additional advantage.

Roadmapping helps people to communicate their plans and visions and to get feedback about them. The communicative part of the process supports thinking about the unknown future, provides knowledge for more informed decisions and is a learning process for the group. Participation in the roadmapping process thus offers benefits for the contributing people and the institutions they are representing. To mention only a few:

- Identify and assess research opportunities, needs and barriers;
- Find knots and cross-links, enabling 'thinking outside the box';
- Structure the research field—visualise complexity;
- Enable and teach interdisciplinary communication which for nanotechnology researchers is of special importance;
- Discover new research options and alternative pathways;
- Support agenda-setting, strategy development and trans-disciplinary communication;
- Make clear communications with sponsors and stakeholders.

Besides this, a successful implementation of this concept could also help to overcome some of the argumentative asymmetries that can be found in many debates about chances and risks of nanotechnology. Very often, in these discussions the–existing or expected–benefits arising from nanotechnology-based or -related innovations are claimed for nanotechnology. However, some of the ideas for products or visions for applications raise also considerable questions with respect to their non-technical implications. Their reference to nanotechnology then is frequently denied, the responsibilities are assigned to the other disciplines involved or other groups participating in the innovation process, a discussion of these consequences in the context of nanotechnology often refused. Such an argumentative asymmetry for many observers leaves the impression of dishonesty or disguise which may lead to public distrust and rejection and support disaster assumptions and dystopic fantasies.

4.3. Roadmapping nanotechnology—the trials

Currently, we are following two different lines to test the applicability of roadmapping in nanotechnology and the quality of the outcomes.

Within the project 'Nano Road SME' that recently has been started, science and technology roadmaps in the domain of nanomaterials will be developed. In the first phase, an international working group integrating roadmap developers, nanomaterials experts and knowledge transfer organisations will build branch specific roadmaps for three different industrial sectors on which nanomaterials are expected to have major influence. In a second step, these roadmaps shall be adapted to the business culture of small and medium enterprises (SME). SME are important drivers of some European industrial sectors and potential users of nanomaterials-based innovations. But they usually don't have either competence or capacity to investigate the potential of nanomaterials for their purposes or to perform a roadmapping process 'in house'. Among other goals, the project aims at structuring the R&D field of nanomaterials, at building a knowledge base for further detailed investigations about the potential of nanomaterials, especially with regard to sustainable development, but also at being a learning experience and serving as a communication tool for the participants. It will be very helpful to observe how the social mechanisms typically involved in the practice of roadmapping will develop in the course of such a trans-disciplinary, multinational, culture-crossing endeavour.

The second effort is currently negotiated to be tested within our own research organisation. We are trying to convince experts from different disciplines and institutes (representing basic research on nanotechnology related phenomena, material researchers and developers, systems engineering, toxicology of nanoscopic structures, systems analysis and project management) to participate in an experiment to develop two science roadmaps using different approaches: The science-driven approach is starting with the current research activities, its results and plans for their continuation and is aiming at opening and assessing technological 'opportunity spaces' for new phenomena and material properties by developing 'property profiles' that can be linked to needs derived either form existing products or to new ideas for application. This will be complemented by a more conventional, application-driven approach where we will be trying to seek and assess alternative (and hopefully better) pathways for one or two yet-to-be-selected products which seem to have the potential to be heavily improved or made possible through the usage of nanomaterials. Some reflections on the role that science roadmapping can play for research organisations, how the experiences with technology roadmapping in companies or industries can be adapted for our purposes, and what further benefits of the roadmapping process beyond structuring the field of nanotechnology can be expected.

5. Summary and outlook

The landscape for Technology Assessment has changed over the last few years. Political priorities are altering and new governance structures are evolving, reflecting growing interdependence and complexity and the need for decision-making under uncertainty. Also, the characteristics of technologies to be assessed are changing. These developments have put pressure on the TA practitioners to rethink their approaches and outputs as well as to review their methods toolbox [15]. This is especially relevant when TA results are expected to contribute to the sustainability assessment of emerging technologies.

Nanotechnology is mainly considered as one of the technological developments to have far-reaching impacts on the industries of this century. Together with the hopes for nanotechnology's exploitation for wealth creation, competitiveness, sustainability and health, growing concerns about its potential to change ways of living, its health impacts and environmental consequences or the threat to stimulate new understandings of 'natural' and 'artificial' or even 'being human' are arising. Nanotechnology is a clear case for technology assessment.

Because of the diversity of scientific and technological approaches pursued under the umbrella of 'nanotechnology', for TA purposes some preparatory steps are needed. We propose an adaptation of the concept of science roadmapping and its application to selected segments of the overall field of nanotechnology. This aims at, inter alia, structuring the research field, linking research activities with visions of products and applications and supporting more reliable judgements on the realism of or hurdles for innovations discussed. Finally, roadmapping could support the conceptualisation of Nano-TA as a 'real time'-investigation and assessment of chances and risk, which has to be closely tied to the current developments in R&D and whose results can be fed back into the scientific, technological and also societal decision-making and agenda-setting processes.

It is not clear to which extent the expected outcomes can really be achieved. There is some scepticism that roadmapping really can fulfil its promises. In addition, some scientists are somewhat restrained about their participation in a roadmapping process. Some fear to disclose too much sensitive knowledge to potential competitors, others think that the application of planning tools to topics of basic research might confine creativity or open the door for more research bureaucracy. On the other hand, there is some experience with similar doubts about the potential of technology roadmapping. In the words of Robert Galvin: "In engineering, the roadmapping process has so positively influenced public and industry officials that their questioning of support for fundamental technology support is muted. . .Just as engineers first scoffed at them (roadmaps, T.F.), so will some scientists. But who better than scientists to experiment with an experiment that can strengthen sciences' support and accelerate its generation of knowledge" [9].

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Torsten Fleischer has a background in physics. After serving as a project manager for several technology assessment studies for the Institute for Technology Assessment and Systems Analysis (ITAS) of Forschungszentrum Karlsruhe, Germany, and the Office of Technology Assessment at the German Parliament (TAB), he is currently heading the project group "Technology Assessment for Nanotechnologies" at ITAS.

Michael Decker studied physics (minor subject economics). After receiving a PhD from the University of Heidelberg in 1995, he worked as researcher at the German Aerospace Center (DLR) in Stuttgart. Between 1997 and 2002 he was a member of the scientific staff of the Europäische Akademie GmbH where he managed several TA-projects and studies dealing with methodological aspects of Technology Assessment. Since 2003 he is a member of the scientific staff and since February 2004 deputy head of the Institute for Technology Assessment and System Analysis (ITAS) at the Research Centre Karlsruhe.

Ulrich Fiedeler is a Postdoc Research Associate in the Institute for Technology Assessment and Systems Analysis (ITAS) of Forschungszentrum Karlsruhe. He has a background in physics with emphasis in the field of semiconductors and solar cells. At present he is working in several projects concerning technology assessment of nanotechnology.