4

EU Nanoroadmap: Issues and Outlook for Technology Roadmaps in the Nanotechnology Field

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1 Background and goals

As part of its Sixth Framework Programme (FP6), the European Commission (EC) created a roadmap for nanotechnology (the EU Nanoroadmap), and published it on a website in January 2006[1]. The roadmap's purpose is to provide a medium- to long-term projection and outline for nanotechnology in three research fields (materials, health and medical systems, energy) through 2015. This report introduces the EU Nanoroadmap and examines probable future issues facing technology roadmaps in the field as well as their optimal form.

Chapter 1 introduces the basic concept of technology roadmaps in general and typical roadmaps for the semiconductor and nanotechnology fields.

1-1 What is a technology roadmap?

In recent years, the importance of innovation in socioeconomic development has become widely recognized. Today's innovation research devotes attention not only to research and development in universities and corporations, but also to the importance of constructing so-called national innovation systems that effectively generate innovation in comprehensive systems incorporating market and social needs, institutions and regulations[2]. At the same time, however, various issues such as latent market and social needs, the appearance of environmental and energy issues, and more advanced and complex technology have arisen.

Amidst these conditions, technology roadmaps are attracting attention as a way of effectively planning and implementing future research and development. A technology roadmap comprehensively examines future market and social conditions and factors such as comparative superiority at home and abroad, aiming to form and visualize a consensus among stakeholders on technologies that should be targeted and on a vision for the future. Advantages of creating such roadmaps include (i) clarification of medium- to long-term research and development strategies, (ii) sharing of unified goals by industry, academia, and government, (iii) promotion of communication and collaboration on research and development that is responsive to increasingly advanced and complex technologies, (iv) technological benchmark effects, and (v) exposure of technological limits[3].

1-2 Technology roadmap development and technology roadmaps in the semiconductor/nanotechnology field

Technology roadmaps originated with the USA semiconductor manufacturer Motorola, which used them in the development and management of new products[4]. Subsequently, IBM and other USA companies adopted the system. During the 1990s, the government and the private sector in the USA created the National Technology Roadmap for Semiconductors (NTRS). At this stage, technology roadmaps had developed from strategy proposal processes inside individual companies to become tools for shared strategies and consultation based on the premise of the development of specific industries. This movement has further evolved into the famous International Technology Roadmap for Semiconductors (ITRS). The ITRS is drawing attention even outside the semiconductor field as the most successful example of a technology roadmap.

In Japan, in addition to the technology roadmaps of major (generally large) corporations, the Strategic Technology Roadmap created and published in March 2005 by the Ministry of Economy, Trade and Industry (METI) in conjunction with related organizations such as the National Institute of Advanced Industrial Science and Technology (AIST) and the New Energy and Industrial Technology Development Organization (NEDO) is well-known. This is the first technology roadmap at the governmental level to take a view of all technology fields. The revised April 2006 version covers 24 technology areas[5].

Furthermore, in the nanotechnology field, the Nanotechnology Business Creation Initiative (NBCI), an organization formed under the leadership of industry to uncover new industries by matching nanotechnology for the 21st century with business, has created business strategy roadmaps for eight nanotechnology areas[6].

Compared with these activities, the creation and promotion of the EU Nanoroadmap, to be discussed in the following chapters, has a similarity to the METI's Strategic Technology Roadmap in that the government provides public funding and it was created as an amalgam of ind ustry-academia-government knowledge. As the name indicates, however, the EU Nanoroadmap covers only nanotechnology and is not a roadmap for any other field.

2 The goals, methodology, and structure of the EU Nanoroadmap

2-1 Goals

Europeans engaged in research and development created the EU Nanoroadmap with the goal of providing knowledge in order to grasp the impact of nanotechnology on society and the economy and more effectively disseminate the results of research and development to the economy and society at large. Therefore, while the roadmap's users include managers and researchers in each sector, its messages for industry are particularly significant. It also emphasizes that small and medium businesses and venture firms are also targeted. The following are also goals of the roadmap.

- Strengthened international competitiveness and expanding markets in the nanotechnology field
- Improved selection, focus, and efficiency of research and development projects
- More effective training and education in the nanotechnology field
- Strengthened national and international collaboration in Europe
- Sustainable development and better quality of life in Europe

2-2 Methodology

Creation of the roadmap took place over two years from 2004 to 2005 in the following two stages. The first stage was carried out during the initial year. It primarily involved the collection and analysis of information regarding nanotech policy and technology trends in various countries and sought to identify the fields where nanotech could be applied based on the results. The second stage involved the actual work of creating the roadmap. The results of each stage can be downloaded as reports from the project's website. In addition, international conferences were held each November to introduce survey results and gather the opinions of participants. An international consortium comprising technology consultants in different areas of expertise from eight EU countries and Israel was formed in order to carry out the survey.

The roadmap itself was created using the Delphi method. There were two question cycles, with the following main processes.

- Selection of leading international experts (Delphi panel)
- Creation of questionnaires for each technology field (including not only questions directly related to technology, but also many questions about examples of applications in society, the economy and industry, barriers to practical use, and technological benchmarks in various countries)

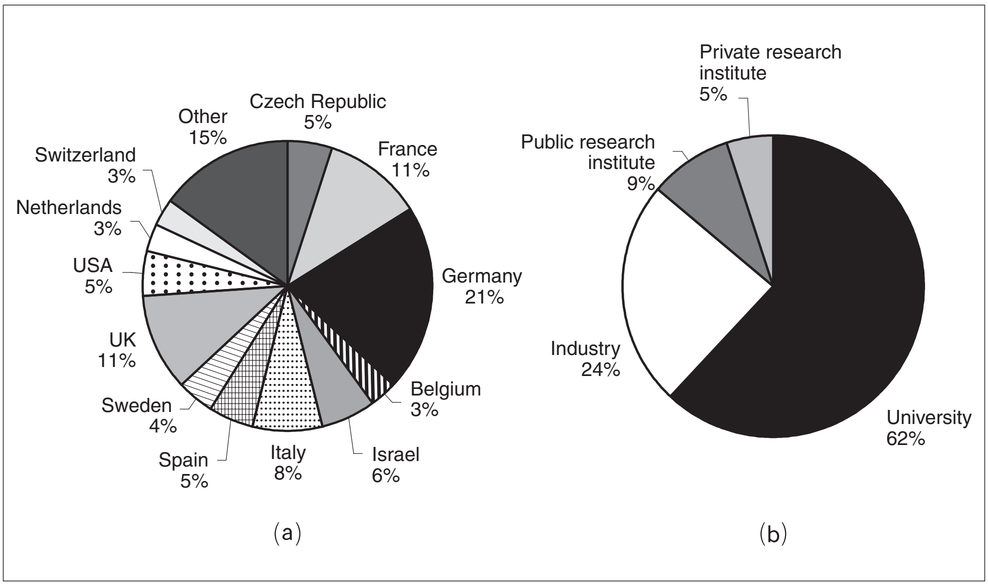

Figure 1 : Nationalities (a) and affiliated sectors (b) of Delphi survey respondents

Prepared by the STFC based on Reference[1]

- Implementation of the first questionnaire (first cycle) using the Internet
- Collection of completed questionnaires and interviews conducted in relation to some of them
- Feeding back the results of the first cycle to the Delphi panel and implementation of the second questionnaire (second cycle)
- Creation of the final roadmap based on questionnaires, interviews, and international conferences

The number of Delphi panel respondents was about 230 (65 percent response rate). Figure 1 shows their nationalities and affiliated sectors.

2-3 Structure

Totaling about 700 pages, the reports can be roughly divided into the following seven reports. Preliminary reports were created and published as Sectoral Reports for the three fields (materials, health and medical systems, energy), while technology roadmaps were created and published as the Synthesis Report for each of the three fields.

The Sectoral Reports investigate technology trends prior to the stage when areas within each field are narrowed down for roadmapping. In addition, they discuss many non-technical aspects such as economic effects, social impacts, and policies in various countries.

The technology roadmaps predict and analyze characteristics of various technologies as well as their advantages and disadvantages, and present their future applications over the coming 10 years. Preparation of the roadmaps centers on the applications of these technologies. The horizontal axis is the development phase (basic research, applied research, etc.) rather than time. The time axis concept is expressed in three maps for five-year periods beginning in 2005 (materials field). Subsequently, technological and social issues and bottlenecks are discussed. The international competitiveness of technology, accessibility of the integrated research infrastructure, need for integrated research facilities, and so on are broadly examined.

3 Content and characteristics of the EU Nanoroadmap: the case of the materials field

In order to discuss the content and characteristics of the EU Nanoroadmap, this chapter will take up the case of the materials field, describing an overview of the roadmap and some other notable features.

In the preliminary surveys, the three fields (materials, health and medical systems, energy) were each covered almost completely, but in preparing the technology roadmaps, each was narrowed down to four areas (Table 1). The narrowing process was as follows. Based on information obtained in the preliminary survey

Table 1 : Areas for sectoral reports and the four areas for technology roadmaps in each field

	Sectoral reports	Technology roadmap
Materials	1) Nanostructured materials 2) Nanoparticles/nanocomposites 3) Nanocapsules 4) Nanoporous materials 5) Nanofibres 6) Fullerenes 7) Nanowires 8) Single-walled and multi-walled (carbon) nanotubes 9) Dendrimers 10) Molecular electronics 11) Quantum dots 12) Thin films	1) Nanoporous materials 2) Nanoparticles/nanocomposites 3) Dendrimers 4) Thin films and coatings
Health and medical systems	1) Tissue engineering/regenerative medicine 2) Bio nano structures 3) Drug encapsulation/drug delivery/drug targeting 4) Molecular imaging 5) Biophotonics 6) Biocompatible implants 7) Biomimetic membranes 8) Biomolecular sensors 9) Biochips/high throughput screening 10) Lab-on-a-chip 11) Functional molecules: switches, pumps, means of transportation	1) Drug encapsulation/drug delivery/drug targeting 2) Molecular imaging/biophotonics 3) Biochips/high throughput screening/lab-on-a-chip devices 4) Biomolecular sensors
Energy	1) Solar cells 2) Fuel cells 3) Thermoelectricity 4) Rechargeable batteries 5) Hydrogen storage 6) Supercapacitors 7) Insulation 8) Glazing technology for insulation 9) More efficient lighting 10) Combustion	1) Solar cells 2) Thermoelectricity 3) Rechargeable batteries and supercapacitors 4) Heat insulation and conduction

Prepared by the STFC based on Reference[1]

during the first year, candidates were proposed to the first international conference (November 2004) in light of the possibility of applying the technology. Following debate by experts, the European Commission discussed and decided on the candidates. The process was the same for each field.

3-1 The technology roadmap in the materials field

First, the technology roadmap in the materials field defines nanomaterials as “novel materials whose size of elemental structure has been engineered on the nanometer scale.” At least one dimension (side, diameter, etc.) must be in the range of 0.1-100 nm.

Because space does not permit discussion of all four areas listed in the technology roadmaps as shown on the right of Table 1, this report will discuss 2) Nanoparticles/nanocomposites (hereinafter, the “nanoparticle area”) as a representative technology from the materials field.

After beginning by defining nanoparticles, the roadmap briefly describes their characteristics (surface, magnetic, and electric properties, etc.). Before showing the actual nanoparticle roadmap, the report divides the nanoparticle research and development pipeline into four stages, production, functionalisation, incorporation into nanocomposites, and application, and explains their technical points in an easy-to-understand way.

First, there is an introduction of the roadmap (overview of applications) for the nanoparticle area in 2005, 2010, and 2015 (Figure 2). To reiterate, the most characteristic feature is that the roadmap’s horizontal axis represents four research and development phases (basic research, applied research, first applications, and mass production) rather than time. The time-axis concept is expressed in three maps for five-year

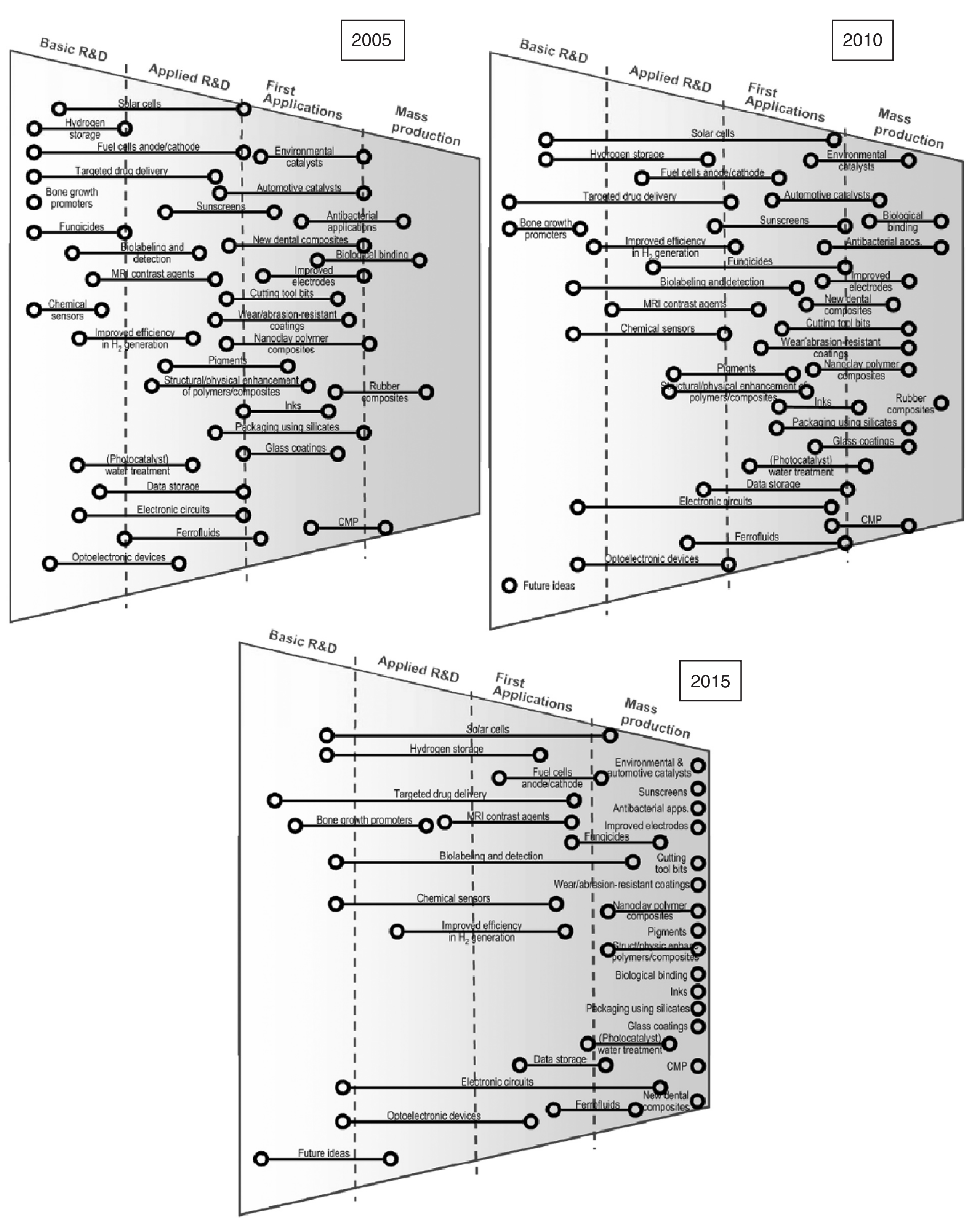

Figure 2 : Roadmap for the nanoparticle area (2005, 2010, 2015)[1]

periods beginning in 2005. Few other roadmaps use this method. For example, in the case of solar cells, shown at the top of the chart, one can see the prediction that primarily basic and applied research will take place in 2005, moving to the first application phase in 2010 and to mass production in 2015. Note that this map refers to nanoparticle applications, so the solar cells referred to (quantum dot, etc.) are different from the silicon crystal and amorphous cells already manufactured.

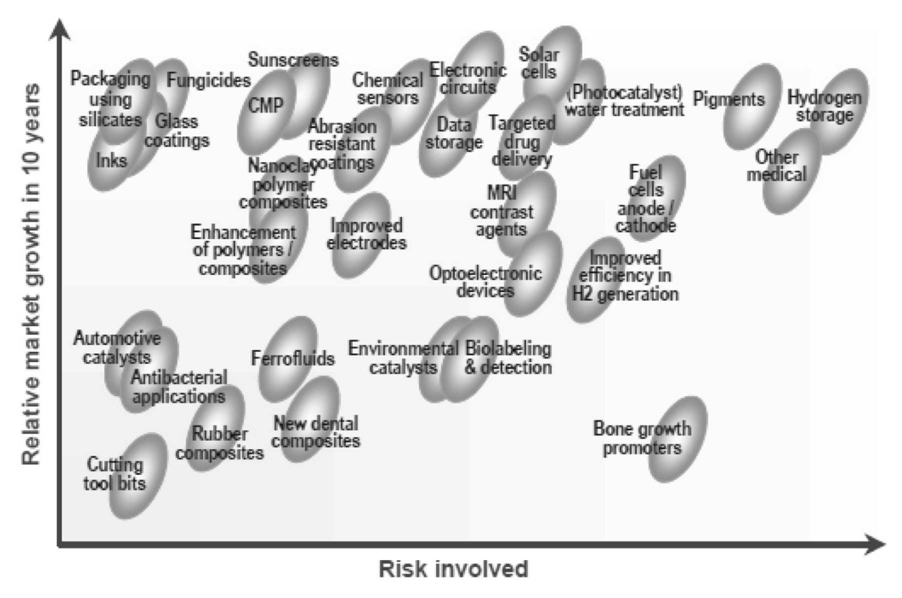

Figure 3 : Technological and economic risk involved with research and development and estimated market growth for the nanoparticle area over the next 10 years[1]

3-2 Technological and economic risk involved with research and development and estimated market growth for the nanoparticle area

Figure 3 depicts estimated market growth over the next 10 years (vertical axis) and technological and economic risks accompanying research and development (horizontal axis) for feasible nanoparticle applications. Rather than risk per se, the horizontal axis can perhaps be thought of as depicting the "depth" of issues and "height" of barriers on the path to practical application. Returning to the example of solar cells, risk is moderate, while estimated market growth is highest of all.

3-3 Self-evaluation of the EU's international competitiveness by type of organization

As mentioned above, non-technical aspects including costs and other economic perspectives, and health and environmental perspectives are discussed extensively. Particularly noteworthy is the discussion of the EU's global competitiveness in each sector. Figure 4 shows the results of the Delphi survey of the EU's international competitiveness in the nanoparticle area. Although the Delphi respondents (Figure 1) saw the EU's technological level in the nanoparticle area as fairly competitive in the academic and large corporation sectors, this dropped somewhat in the small and medium enterprise and startup sectors. (Fewer than half of respondents chose "Excellent" or "Good.") This tendency applies not just to the nanoparticle area, but to nanotechnology as a whole. It is interesting to see that the experts find the EU's industrial technological level (especially for small and medium enterprises and startups) to be deficient compared to the rest of the world. Furthermore, the survey design itself emphasized (saw as an issue) small and medium enterprises and startups. This also indicates the importance of small, medium, and startup companies in the EU's view of the nanotech field.

In addition, the preliminary survey carried out in advance of the preparation of the technology roadmap shows outlooks for current and future markets and applications along with trends in research and development activities in leading countries for the 12 technology areas shown in Table 1 based on public documents from more than 30 countries. Although this report cannot go into detail, it is interesting to see the EU's view on world research and development activities. One example is the discussion of research and development trends in the leading countries for the carbon nanotube area. Although carbon nanotubes (CNT) were discovered in Japan, the discussion never touches on this country. Covering several pages, it mainly addresses European and US universities and some corporations. It also refers to South Korean and

Taiwanese firms (Samsung and TECO Electric and Machinery) that have applied CNT to displays as well as mentioning the Indian Institute of Science and the results of its application of CNT to gas flow sensors.

3-4 Patent system issues in the EU and the USA

Among the Delphi survey questions for the materials field, one asks how differences between the EU and US patenting systems might lead to disadvantages for EU nanotech development in the medium and long terms. Figure 5 shows the results. Although there were no detailed analyses or proposals in the text, 76 percent of the experts displayed anxiety regarding the less restrictive US patenting system.

3-5 Recommendations for the materials field

Finally, this roadmap offers three recommendations for the materials field. First, promotion of up-scaling of materials process technology. This would increase technology reproducibility, control manufacturing costs, and raise recycling efficiency, building sustainable systems. Second, increased risk capital for product development startups. This would promote high-risk, high-return research and development as well as establishing and expanding markets with the unified support of large corporate manufacturers and corporate investors. Third, establishment of nanotech research and development centers. This would be especially beneficial to startups and small and medium enterprises. Regarding the establishment of nanotech multidisciplinary centers, the Delphi survey also found that a large majority of experts supported the idea (Figure 6). Such multidisciplinary centers would be effective not only for the integration of technologies, but also for increasing the liquidity of technology among all sectors, small, medium, and startup businesses, large corporations, and public

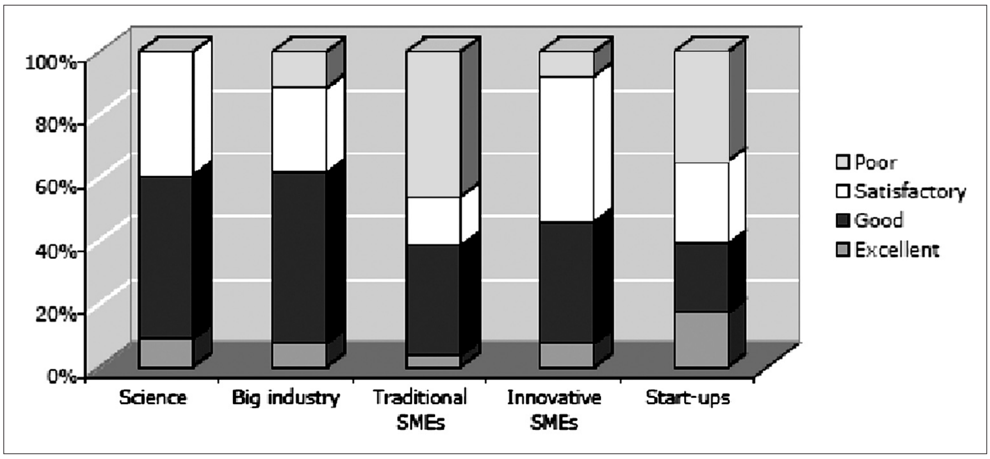

Figure 4 : Results of Delphi survey on self-evaluation of the EU's international competitiveness by type of organization (nanoparticle area)[1]

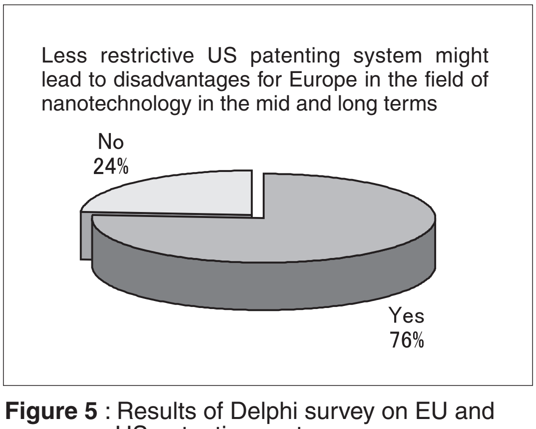

Figure 5 : Results of Delphi survey on EU and US patenting systems

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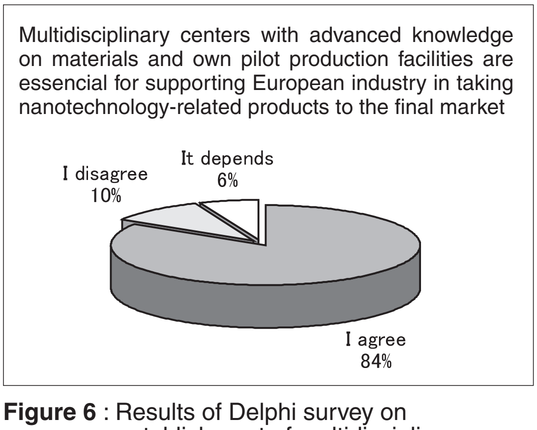

Figure 6 : Results of Delphi survey on establishment of multidisciplinary centers for EU nanotech industrial application

Prepared by the STFC based on Reference[1] entities, and reducing the time cycles to market.

The need for such multidisciplinary centers was also pointed out in the other two fields (health and medical systems, energy).

3-6 Conclusion: characteristics and aims of the EU Nanoroadmap

As discussed, the EU Nanoroadmap is more complete in terms of its social and economic perspectives than as technological analysis. Because the roadmap is a report intended to contribute to strategic planning on a wide regional level, the EU's characteristic tendency to advance a social agenda makes an appearance. In particular, the field of nanotechnology is expected to play a role in achieving the goals set forth in the Lisbon Strategy of March 2000[7]. In addition, the roadmap also looks to the Seventh Framework Programme (FP7), which will begin in 2007, seeking to clarify nanotech strategies and highlight problems. As noted above in Chapter 2, the roadmap carries a strong message for industry, especially small and medium enterprises and startups. This can therefore be supposed to be the reason for an emphasis on certain aspects of research and development and noteworthy items for each technology and on understanding and discussing trends for nanotechnology as a whole in the EU rather than on deep explanations of individual elemental technologies.

4 Technology roadmap issues and outlook for the nanotechnology field

This article has described the EU Nanoroadmap, using the materials field as an example. In conclusion, we will address issues facing technology roadmaps in the nanotech field and the outlook stemming therefrom based on the author's own knowledge and the following perspectives.

4-1 The problem regarding uncertainty of technology and industrial application in nanotechnology

Nanotechnology is an emerging multidisciplinary field. Preparation of technology roadmaps therefore faces difficult problems different from those of other fields. The current industries active in research fields such as nanotech that aim to construct new industries are immature. One might even say that every technology in the field has the potential for industrial application. In other words, the uncertainty of technical realization and the uncertainty of markets make it extremely difficult to map out connections among technologies and products. Even supposing the existence of shared social and market goals, it is not easy to categorize them as research themes in a specific nanotech field. It is difficult for researchers and managers to judge which technology seeds would lead to those goals being attained, or even to determine what (effective) seeds exist. They face an apparent "latency of seeds"[*1, 2].

Table 2 shows technology classifications devised by Yasunaga, et al., with technology structuring and shared awareness of future markets as axes[9]. In the semiconductor field, where technology roadmaps have been most effectively used, although technological evolution centered on miniaturization has been remarkable, the technology structure itself has changed little in about 30 years, and stakeholders have a shared awareness of markets. On the other hand, future markets and technology structures are both unclear for nanotechnology, and this is the difficulty in preparing roadmaps for the nanotech field. Furthermore, depending on the awareness of preparers and users, risks may appear. Nanotech roadmaps must therefore be careful to avoid narrowing the potential of nanotech more than necessary even as they seek to clarify strategy. Concrete measures that can be taken to address this include annual revisions, creation of maps that use the "functions" and "characteristics" likely to be demanded of materials in the future as axes, and clarification of goals by strengthening integration with roadmaps for other fields. In addition to such measures, preparers and users must be fully aware of the issues and risks involved with nanotech roadmaps.

Regarding these points, the EU Nanoroadmap discussed in this report handled them by narrowing down its technology fields, taking care to map only applications and realization,

Table 2 : Technology classifications with technology structuring and shared awareness of future markets as axes

Technology \ Future market	Shared awareness	Insufficient shared awareness	
		Opacity of market	Opacity of social vision
Structured	• Semiconductors	• Consumer robots	• 3R
Not structured	• Regenerative medicine • Genomic drug discovery	• Nanotechnology	• Green sustainable chemistry

Prepared by the STFC based on the Reference[9]

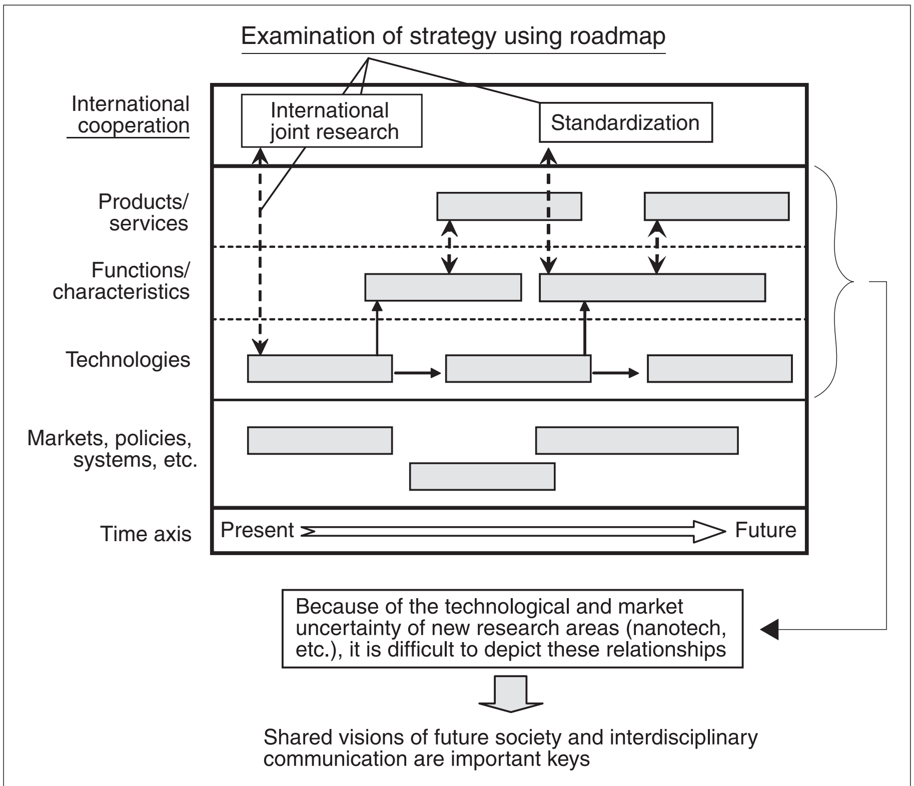

Figure 7 : Issues and international corporation for nanotechnology roadmaps

Prepared by the STFC

mapping paths to realization by dividing its horizontal axis by research phase rather than time, and narrowing its points of debate to the extraction of (social) issues anticipated upon practical realization. Furthermore, in order to create new values through nanotechnology, the Delphi results indicate experts' need to form multidisciplinary research centers (Figure 6).

4-2 The international role of technology roadmaps: competition and cooperation

Finally, this report will offer proposals from an international perspective. Over the past several years, various governments and joint bodies have prepared an abundance of technology roadmaps from the standpoints of clarification of research and development strategies, compilation of knowledge from various sectors, and the obligation of explaining these matters to the public. Naturally, these initiatives in various countries have proceeded in parallel with one another, and collaboration among them has not yet been undertaken. At this stage, therefore, countries and regional confederations such as the EU are preparing roadmaps in order to raise industrial competitiveness. However, these technology roadmaps being simultaneously prepared could become unparalleled tools for international cooperation. The nanotech field in particular is likely to become the focus of active international standardization and joint research and development. Study based on the technology roadmaps of both sides may yield better results for both through more efficient debate, comparison of technology seeds, and differentiation of applications. Furthermore, with the field's technologies becoming more advanced and complex, there are some that can be realized with domestic resources and some that require cooperation with other countries. For technologies for which international collaboration is thought necessary, expansion of the scope for roadmap preparation to include technical development partners and feasibilities should be discussed (Figure 7).

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Notes

*1 In Reference[3], Yasunaga, et al., place the layer "function" between "technology" and "new values" in roadmaps. Functions serve to mediate between technology and values. Furthermore, technologies not noted in maps do not mean unimportant. Instead, constant revision of maps is necessary.

*2 In "Open Innovation"[8], Chesbrough, et al., point out that increasing uncertainty in technologies and markets in high-tech industries makes the integration of technologies developed by outside organizations vitally important. The degree to which this perspective is incorporated in nanotech roadmaps is a major issue.

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