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Bridging the gap between foresight and market research: Integrating methods to assess the economic potential of nanotechnology ☆

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Abstract

This paper discusses how to bridge the gap between foresight research oriented to the long-term, and traditional market research oriented to the medium to short term, when applied to an early stage of a technology's life cycle. It proposes using an integrating approach, i.e. a combination of methods and both foresight and traditional market research. A mix of complementary methods for the acquisition and analysis of data is presented in a case study. This helps to overcome the deficits of some qualitative foresight methods and quantitative methods often used in traditional market research and allows us to examine research results from the different methods applied both on their own and as a group. In the absence of a single fully-fledged and accepted economic approach, this paper argues that combined *market research* and *foresight modules* are the best possible approach for analyzing the economic potential of emerging technologies like nanotechnology. In the future, similar applications of such

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market foresight modules may be useful, for example, as elements of foresight. They will also be useful in studies of emerging technologies (e.g. converging technologies, cognitive science and Web 2.0) where traditional market research does not produce a realistic market assessment.

Keywords: Traditional market research; Foresight; Nanotechnology; Integrating research methods; Emerging technologies

1. Introduction

Foresight is usually seen as a systematic collective process of reasoning about the future, which suggests possible courses of action. Quite often it is a participatory process involving the stakeholders concerned with a particular issue. It always envisages a number of alternative futures, and has a typical time horizon of 10–20 years.[1] The benefits of foresight are threefold. Firstly, the involvement of relevant actors in the debate creates ownership and orients actors towards policy objectives (*soft coordination*). Secondly, the joint learning process as results from the foresight activities leads to better connectivity in the innovation arena through networking and improvement of knowledge flows [3]. This leads to better innovation capability. Finally, anticipatory intelligence is created from a wide diversity of viewpoints and knowledge sources, which serves as a base for future-oriented decision making. In particular, technology foresight is “an instrument of strategic policy intelligence which seeks to generate an enhanced understanding of possible scientific and technological developments and their impact on economy and society” [4]. It does not focus on technology in a narrow sense but sees technological change as being embedded in broader change in the economy and society. It therefore “provides a process for linking science and technology more effectively to wealth creation and improvements in the quality of life” [5].

Foresight has long since moved away from the early predictive “forecasting approaches”, based on trend extrapolation and expert consultations, towards a “third generation of foresight” [6]. This takes a holistic view and applies a wide range of methods to structure stakeholder dialogue to create collective intelligence. Technology forecasts, which provide information about technological trends are, however, still an important input into the foresight processes. *Traditional market research* differs from foresight in many respects. Not only is the time horizon much shorter (usually 5–10 years) but also the purpose is different. While foresight orients decision making (for policy and also business) in a general way and only in specific cases does it lead to concrete strategy building [7], traditional market research can be used for concrete short to medium-term company business and strategy planning [8,9].

In this paper, we discuss a study on the economic potential of nanotechnology, which uses elements from both foresight and traditional market research. The study was carried out by an interdisciplinary team of economists, social scientists, engineers, physicists and chemists over a period of 2 years. It aimed to assess realistically the market volume and relevance of nanotechnology, both in Germany itself and in an international context. It also aimed to bridge the gap between foresight and traditional market research, by doing empirical research on the economic potential of a specific emerging technology and *using methodological elements of the traditional market research module and the foresight module*. We will use the example to show how elements from both modules can be combined to create a better understanding of the future development and diffusion of emerging technologies. This combination yields a somewhat

[1] See FORLEARN online foresight guide [2].

broader understanding than traditional market research, and also more quantifiable outcomes, which are more suitable for the orientation of business investments than foresight research.

2. The subject: economic relevance of nanotechnology

Nanotechnology is one of the emerging and breakthrough technologies of the 21st century. Rather than a clearly defined base technology in the classical sense, it is an interdisciplinary science domain with potential applications in electronics, optics, and new materials. On the one hand, nanotechnology engineering works with active and inactive elementary units, i.e. atoms and molecules, and is comparable to a Lego kit (*bottom-up*). On the other hand, it is possible to create structures measuring as little as one thousandth of the diameter of one hair by means of miniaturization (*top-down*).

An internationally standardized concept that defines nanotechnology does not yet exist. This article has adopted the following definition, used by German Federal Ministry for Education and Research (BMBF) in its official publications [10]:

> "Nanotechnology describes the creation, examination and application of structures, molecular materials, inner interfaces and surfaces with at least one critical dimension or with manufacturing tolerances (typically) below 100 nanometres. The decisive factor is that new functionalities and features for the improvement of existing products or the development of new products and application options result from the nanoscalability of the system components alone. These new effects and possibilities are predominantly based on the ratio of surface to volume atoms and on the quantum-mechanical behaviour of the matter elements".

Nanotechnology is a good *case study* for foresight and other future-oriented approaches[2] and market research. There are several different possible long-term patterns of societal change associated with the embedding of nanotechnology into society that need to be considered in stakeholder debate.[3] At the same time, it is important for companies already active in the field and for policy makers aiming to secure competitiveness to identify potential future applications in this innovation area. The speed of innovation in nanotechnology has meant that the first product groups are entering world markets even before their physical fundamentals are fully understood. In many ways, it is only by manipulating matter that scientists start to grasp its self-organising principles. The industrial breakthrough will come when nanoscale architecture is implemented in macroscopic devices for new functions. Foresight and other future-oriented studies and traditional market research studies published so far are still too fragmentary to portray precisely the economic importance of nanotechnology for all lines of industry concerned, particularly as the definition remains vague [13–16]. The basic assumption of this article is that the economic potential of nanotechnology can hardly be assessed realistically by purely quantitative or qualitative methods of empirical research, due to the complexity and vagueness of the definitions of nanotechnology which is still an emerging technology in the early stages of development. Moreover, any assessment of this technology without understanding societal expectations would be unrealistic. Therefore, we argue there is a need for an integrative approach to bridge the gap between foresight and traditional market research when performing empirical research on the economic potential of emerging technologies and their impact.

[2] The most applied future-oriented approaches are: foresight, technology forecasting and technology assessment [11].
[3] See for instance the scenarios in the European Nanologue project which started in 2005 [12].

3. Methodology employed

According to Alemann [17], qualitative (e.g. expert interviews, literature reviews, expert workshops) and quantitative methods (e.g. standardized surveys, patent analysis) are nowadays to be regarded as complementary rather than competing methods for gaining insights after years of debate. Open procedures for qualitative methods, are preferred as they impose fewer restrictions on people when asked to formulate their subjective reality constructions. In quantitative methods, standardized measuring instruments are usually applied to quantify the measured variables and analyze them, with the help of statistical methods. Meanwhile, there is a growing conviction that: "there is no ideal method solution for empirical research. Instead, a combination of (traditional market research and foresight) methods has to be applied, especially qualitative and quantitative methods that take into account the subject area, the problem concerned and the available financial and time resources" [18]. *Integrating research methods* has proven to be useful in one other case: the evaluation of the potential of microsystems engineering [19]. The assessment of the economic potential of other emerging technologies like, for instance, biotechnology or new energy technology, is only similar to some extent, although combined methods are also used. These assessments may have too strong a focus on quantitative methods and be a little too narrow in scope, leaving societal expectations to one side [20]. Alternatively, they may focus too much on qualitative methods and lack economic data [21].

4. Work phases

The first phase of the study was dedicated to collecting background information. The existing body of foresight and market studies on the subject was analyzed (*literature review*) and a *preliminary patent analysis* carried out, using a broad definition of nanotechnology. Furthermore, we conducted 15 *exploratory expert interviews* (*work phase 1*). The information derived was used to define a standardized questionnaire for a *business survey*. Before its application, the questionnaire underwent a pre-test. The outcomes were analyzed with the help of the statistical programme SPSS. Furthermore, through *in-depth examination* of information about *inventors and patent applicants* available in the relevant databases (e.g. WPINDEX, EUROPATFUL, USPATFUL), knowledge about the role of German enterprises and scientists in this field was gained (*work phase 2*).

The research results from the literature review, patent analysis and business survey (from work phases 1 and 2) can be described as *results of the traditional market research module*. These were formulated as theses and used as the basis for constructive discussion in 4 *branch-specific expert workshops (Delphi method)*.[4] This can be described as the *first element of the foresight module*. The workshop participants were from banks, science, nanotechnology competence centres, producers, suppliers, system developers and venture capital enterprises. These experts gave a critique of the outcomes from the literature review, patent analysis and business survey. They also contributed their expert knowledge about the economic potential of nanotechnology from their respective points of view. In order to estimate the importance of nanotechnology for the major German markets (*lead markets*), special attention was paid to those businesses that have a major influence on the technological competitiveness of German industry

[4] In the Delphi method, experts of the respective field to be examined are polled, as a rule in one or more runs. They are mostly presented with an explicitly structured catalogue containing questions and theses, on the basis of which they are to make their assessments of future developments and trends [22].

(chemistry, car manufacture, optics, life sciences and electronics). The experts were also asked to comment on some important statements concerning societal acceptance and non-acceptance of nanotechnology. For instance, one statement concerned the impact of uncontrolled release of nanoparticles and the demand by some social interest groups for a moratorium on development, in order to raise awareness among scientists and industrialists of possible *societal expectations* (hopes and fears). The data gained was processed again by the project team and put before the respective branch-specific expert networks for validation before its final documentation (*work phase 3*).

Based on the compiled information and with the help of another structured method (*SWOT analysis*), which can be described as the *second element of the foresight module*, an analysis of the status of nanotechnology in Germany (*Strengths and Weaknesses*) and the existing *Opportunities and Threats* was carried out by the experts who attended the 4 workshops (*work phase 4*). The whole process of the comprehensive mix of methods (*traditional market research module* and the *foresight module*) to assess the economic potential of nanotechnology presented in this paper is visualized in Fig. 1.

The methods used for the collection of information on current trends and developments (literature review, patent analysis, expert interviews and business survey) are routinely used in traditional market research. They are also a vital element in foresight (under the heading of *environmental scanning*) for the collection of information to be fed into the collective learning process, usually in the first stage (*diagnosis phase*). However, in this study the expert workshops served as means for synthesizing the information that was generated jointly with a group of stakeholders using *a typical foresight method – the Delphi method – to structure the process*. Doing it this way and making use of the participants' rich diversity of perspectives, it was possible to generate an integrated understanding about the economic impact of nanotechnology. Furthermore the *process benefits* – associated with foresight but not with traditional market research – such as networking and building consensus on the issues at stake, were clearly achieved, although – due to the limited number of participants and events – *no fully-fledged foresight* was carried out. The *SWOT analysis*, also an *essential component of foresight methodology*, led to the *generation of further collective intelligence*. The key methodological element which served to integrate quantitative (patent analysis, business survey) and qualitative analysis (stakeholder dialogue) was the *transformation of the background information into Delphi statements* thus linking the market research module with the foresight module. In doing it this way the data became accessible *for future-oriented collective reasoning*. In the following paragraphs the individual steps of the analysis will be discussed.

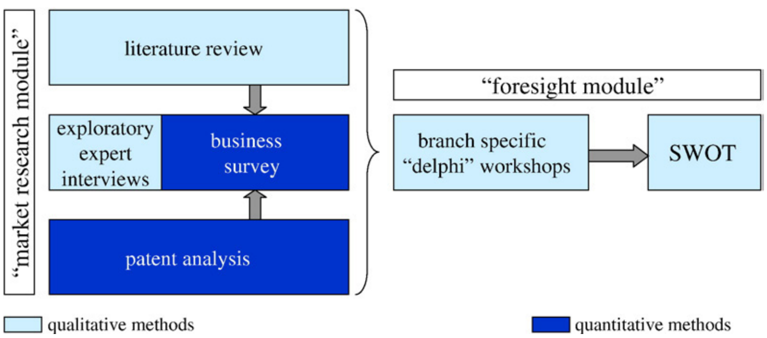

Fig. 1. Integrating market research and foresight modules to assess the economic potential of nanotechnology.

5. Foresight and market research on nanotechnology

5.1. Research method: literature review

The analysis of nanotechnology applications and their market prospects in products and product groups was based on a *secondary analysis of foresight and other future-oriented studies and market research publications*. The following sources were used:

- Market and foresight analyses and press releases of different market and foresight research institutes, partly with specialization in the field of nanotechnology, e.g. Business Communication Company (BCC), CMP Científica, Buero fuer Technikfolgenabschaetzung (TAB), Fraunhofer Gesellschaft (FhG);
- Press releases and publications of enterprises;
- Publications in special journals, the daily press and on the Internet.

Apart from a *qualitative description of the application potential, quantitative statements concerning the market potential of nanotechnology* were also made, albeit with the proviso that quantitative evaluation of market potential is complicated by the fact that the nanotechnology field has the following characteristics:

- Nanotechnology cannot be assigned to classical industry classification as it is a cross-sectional discipline, which is used in different sectors of industry.
- It does not represent a uniform technological platform, but comprises a wide spectrum of various fields of technology and research (e.g. materials technology, coating technology, nanostructuring, analytics and surface treatment).
- Nanotechnological processes and products predominantly start at the beginning of the value-added chain and mainly refer to individual components only, the functionality of which is enhanced by nanotechnology. The share of nanotechnology in the value added of marketable products is hardly quantifiable or can be recorded only vaguely.
- For the most part, nanotechnology is still in the research stage. Evaluations of the market success of future product options and visions are therefore more or less speculative.

5.2. Research findings

Fig. 2 shows the span of published market figures regarding nanotechnology which range from 900 million USD for the world market volume of nanostructured materials in 2005 [23] to one trillion USD for the world market volume of nanotechnologically-influenced products in 2015 [24].

In order to evaluate market figures more accurately and to avoid misinterpretations, it was necessary to first discuss the following questions:

- Which definition of nanotechnology was used?
- Which databases are the figures quoted based on?
- Which (sub)areas of nanotechnology does the market evaluation include (e.g. nanomaterials, nano-coatings, tools and measurement technology for the generation of nanostructures etc.)?
- To which value-added stage do the market figures refer (elements such as nanopowder, intermediate products like laser diodes, or end user products like computers or domestic appliances)?

World market (year)	With regard to	Source
493 million USD (2000) 900 million USD (2005)	Inorganic nanoparticles and powders (metal oxides like SiO_2, TiO_2, metals etc.)	[23]
1 trillion USD (2015)	Nanotechnological products	[24]
40 billion USD (2002)	Synthetic nanoparticles as primary products	[25]
23 billion USD (2003) 73 billion USD (2003)	Nanomaterials Nanotools, Nanodevices + Nanobiotec	[26]
7 billion USD (2002) 28.7 billion USD (2008)	Nanotechnological products (mainly nanomaterials, furthermore nanodevices and tools)	[27]
54 billion EUR (2001) 100 billion EUR (2005)	Nanotechnological products (classified according to nanomaterials, nanolayers nanoanalytics, ultraprecise surface treatment, lateral nanostructures)	[28], [29]
66 billion USD (2005) 148 billion USD (2010)	Nanotechnological products	[30]
Up to 200 billion EUR (2005)	Nanotechnological products	[31]

Fig. 2. Outline of market figures and forecasts for nanotechnology [25–27,30,31].

The market forecasts of the Business Communication Company (BCC) [23] and the American National Science Foundation (NSF) [24], mentioned above, represent two extremes. While BCC forecasts are confined to a limited section of nanotechnology (inorganic nanoparticles) calculating the market value of the elements, NSF forecasts refer to the market value of all end products that are somehow influenced by nanotechnology (e.g. medicine, computer, data storage etc.). NSF forecasts neither mention specific products nor specify the share of nanotechnology in the added value. Another factor of uncertainty is the time horizon. Therefore, it is not surprising that market volumes predicted may differ by a factor of 1000.

Between these two extremes, there are other market forecasts that segment nanotechnology into different sub-areas (nanomaterials, nanoanalytics, etc.) and determine the market potential of nanotechnology by adding up the market value of specific products that contain nanotechnological components [28,29]. For products that have not yet reached market maturity, the substitution potential for existing products is usually given (e.g. MRAM-memory chips as substitutes for DRAM-memory chips). In cases where the value-added share of a nanotechnological component in the end product is not quantifiable, or market data is not available, the *value of the smallest sellable unit* of a product that contains the nanotechnological function is stated. For example, in the case of hard disk data storage, this would be the whole disk drive, although only the GMR reading head contains a nanotechnological function.

Market figures may also be distorted by double counting of nanoproducts. For example, it may be that products from different value-added stages are repeatedly brought into the evaluation, even though they are based on the same nanotechnological basic product. Therefore, it is possible that, for example, to determine the total market volume, a nanocrystalline material in a product (e.g. sun cream) is brought in both at the value-added stage of the raw material (nanocrystalline material) and at the end-product stage (sun cream). This double counting leads to an overestimation of the market size.

6. Nanotechnology and patents

6.1. Research method: patent analysis

It is accepted that patents can be very valuable and play a central role in company competitiveness.[5] Less importance is given to the fact that many patents are of hardly any value. Ironically, these patents only run up costs. Scientific literature describes a lot of methods for the evaluation of patents in different situations [33,34]. Patent evaluation is necessary to support management decisions during R&D projects and for their commercialization, as it poses questions such as:

- Should an invention be patented?
- Should a patent application, once initiated, be followed up? If yes, in which countries?
- Should a patent, once granted, be maintained? If yes, in which countries?

However, patent evaluations are also important within the framework of license negotiations, for the sale of patents, in negotiations regarding venture capital for start-up companies, the sale and merger of companies, and for the balancing of accounts and reporting. In the end, the value of patents is determined according to the future market value of the products concerned. Accordingly, the *patent evaluation itself is based on some kind of market forecast* and therefore *subject to all the uncertainties inherent in such a forecast*. Since even the relation to the respective products is not always clear, the uncertainties arising from forecast patent evaluations are particularly pronounced. So patent evaluations are dependent on the point in time they are drawn up and are subject to changes over time, if, during this time, the basis for evaluation has also changed.

As has been proved, several bibliometric patent indicators correlate with the value of patents [34]. They have the advantage of being reliably collectable from patent databases at manageable costs. However, the use of patent indicators implies that relevant patent information has already been published; hence it requires certain forward planning. In practice, *the number of quotations in search reports and third-party patents are used*, as well as the *number of objections*, the *number of references in non-patent literature*, the *existence of appeals and nullity suits*, data about the *scope of patent families* and the *status of patent grants*.

Just as there is no generally accepted definition of nanotechnology, neither is there an accepted enquiry strategy for nanotechnology patents. Even the studies mentioned above differ considerably in terms of search words used. A distribution on the basis of special classes in the international patent classification

[5] As a current example, the decision of the Tokyo district court has to be mentioned, which obliges the company Nichia to pay 180 million US dollars to Prof. Nakamura, the inventor of the blue light-emitting diode [32].

(IPC) is not possible either. The *multitude of enquiry strategies* in literature can be roughly subdivided into the following three groups:

1. The most simple strategy is *searching for the prefix "nano"*, with certain combinations of this prefix being excluded explicitly when there is obviously no connection to nanotechnology. The most frequent of these combinations to be excluded are: nanosec? or nano2 or nano3 or nanogram? or nanolite? or nanolitr? or nanomol? or nanos or nanosat? or nanosec? or subnanomol? or subnanosec?
2. A detailed search strategy comprises the *compilation of comprehensive search word lists*. Examples are to be found in Braun et al. [35] and Compano/Hullmann [36]. In principle, explicit search word lists consist of two elements. First, there are search words representing nanotechnology in its entirety, if possible (example: "nanoparticle"). Second, there are search words that are typical for individual partial technologies that are regarded as belonging to nanotechnology. The difficulty of such rather specific search words is the compilation of a complete list. Depending on the partial technologies considered or ignored in the search, distortions and imbalances may arise, especially if the companies that apply them are found to be companies with a very specific product and technological profile. On the other hand, with the number of additionally considered partial technologies, there is a growing risk of including search words that do not only describe nanotechnology.
3. The most thorough strategy is to *carry out a wide-ranging enquiry of a comprehensive sample* of applicants for nanotechnology patents, and to decide whether they belong to nanotechnology after an examination of all the patent specifications investigated.

For the patent analysis,[6] the WPINDEX database was chosen. This has two advantages:

1. WPINDEX is suitable for statistics, as each individual element of the database portrays a complete patent family. This is not the case in other databases, in which multiple registrations of the same patent application are possible (e.g. when publications of unexamined applications and patent specifications for the same application, as well as equivalent specifications of the same family, are registered as separate documents in a database).
2. The database provider draws up its own short summary for each patent family. This moderates the consequences of the common practice for patents to deliberately avoid essential keywords (here e.g. the prefix "nano") in the patent wording.

6.2. Research findings

Evaluation of patent applications over several years confirms that they reflect nanotechnology's extremely dynamic progress. During the last 5 years, the number of patent applications in nanotechnology doubled almost every 2 years. As a country, Germany is in a very good position regarding nanotechnology patents — both in nanotechnology as a whole and in the numerically most important sub-field of chemistry. Germany is keeping up with both the USA and Japan in all of its lead markets (chemistry, car manufacture, optics, life sciences and electronics).

[6] Due to the large number of patent documents and the limited resources available, a search based on a detailed word list was selected for the purposes of this study, for example: nanoactuator?, nanoaggregate?, nanoamorphous?, nanoanaly?, nanoarchitectur?, nanoarray?, (w) organ (w) vapo? (w) phase (w) epitax? or movpe.

In the branch-specific expert workshops (*Delphi method*), *discussion centred around patent strategies* in the field of nanotechnology. Industry experts pointed to the fact that, basically, *nanotechnology does not require a totally different patent strategy* than other fields of emerging technology. However, a *special feature* is that *development times from a new nanotechnological basic effect to its application may be so long* that, in certain cases, the *patent protection expires shortly after product maturity* has been reached. This is in sharp contrast to some other technologies like Information and Communication Technology, where time to market is much shorter. In the workshops, industry experts pointed out that the tendency to patent in small to medium-sized enterprises (SMEs) is significantly lower than in large-scale enterprises. SMEs prefer not to disclose any technological trade secrets they may have, — even if they are patentable. If in doubt, SMEs would rather register utility patents which are cheaper.

The analysis of bibliometric patent indicators cannot provide an assessment of the market potential in absolute figures. However, it becomes clear that considerable efforts to secure intellectual property in the field of nanotechnology are being made worldwide — a fact that suggests that patent applicants see a significant market potential in this field.

7. German companies and nanotechnology

7.1. Research method: business survey

Nanotechnology is considered to be one of the breakthrough technologies of the future. However, the full scale of the possibilities of nanotechnology is not yet visible. Indeed, up to now, only the first steps towards innovations through nanotechnology have been taken. Against this backdrop, the *paper-based business survey* aimed to clearly identify the economic potential of nanotechnology in Germany, and carry out a (first) evaluation. The central questions of the quantitative company survey were, inter alia:

- Where is nanotechnology already used today?
- What growth potential do economic players expect nanotechnology will have in the years to come?
- And finally, what relations already exist between economic players in nanotechnology today?

In order to measure these aspects, the *whole business survey was based on a uniform definition of nanotechnology* (see Section 2). The questions for the questionnaire were formulated to elicit information on three development stages of nanotechnology companies:

- Their behaviour in the past,
- their current procedures,
- and their strategic orientation.

Moreover, the wording of the questions ensured that the focus of a company's activities in R&D, its product range, the supply of nanotechnological components, and the networking involved in this supply, were scanned.

The Future Technologies Divison (FTD) of the VDI Technology Center supplied approximately 450 addresses of selected companies in Germany that could clearly be assigned to nanotechnology.

Public scientific institutes were not included. The Deutsche Bank contributed an additional 291 addresses, mostly of companies active in Microsystems Technology (MST), which comprises a set of technologies at the interface with nanotechnology. Therefore, it can be assumed that, of approximately 800 addresses, some 450 to 700 addresses are of companies that are active in the field of nanotechnology.

Depending on the figure the parent material is based on, and on the evaluation of the returns, different return rates result.[7] The margin ranges from 13.1 for 105 completed and processed questionnaires in relation to approximately 800 questionnaires sent out, to 15.0 (700 company addresses) and 27.1 for 122 (107 plus 15 “no activity in the field of nano”), in relation to the approximately 450 company addresses of the VDI TZ FTD parent material. Since nanotechnology is still in the early phases of commercial exploitation (i.e. its prospects are developing only gradually), from a research point of view this *results-oriented selection of the parent population was clearly superior* to a purely random sample of companies. The return rate was sufficient for achieving secure and representative statements with the help of quantitative processing because the *companies that answered represented a miniature copy of the given population* [37] of small, medium and large companies active in nanotechnology in Germany. For this reason, a *non-response analysis was not mandatory.*

7.2. Research findings

The analysis of the business areas of the companies polled showed that companies dealing with nanotechnology were mainly active in the chemical industry and the manufacturing of measuring, control and navigation instruments. This coincided with the results of other surveys. According to the results of the business survey, the period in which the highest number of companies went into the “nanotechnology business” was from 1996 to 2000. In this period, the observation of the nanotechnological scene, companies’ own R&D work, and nanotechnology use in products experienced the sharpest increases. Public discussion of market relevance (1996) for instance, and the establishment of competence centres (1998) for the field of nanotechnology, initiated by the BMBF with public funding, also fall into this period.

The number of companies making their first sales with products containing nanotechnological components and companies achieving their total sales with products with nanotechnological shares increased significantly. It has to be emphasized that 66% of the companies described themselves as manufacturers and about 29% as purely users of nanotechnological products. Consequently, the group of companies that only use nanotechnological primary products has played a less important part so far compared to the group that actively manufactures these components. This pattern is typical of a technology diffusion process. Thus, it was a good sign for ongoing diffusion that the number of users acting purely as market observers without achieving sales with nanotechnological primary products decreased from 71% in 1996 to 25% in 2001.

While the analysis of the supply of primary products suggests that *Germany has reached a good position in the field of research*, companies in the USA seem to be faster in transforming research results into products (e.g. in the field of ICT). It is also interesting to note that, currently, hardly any German

[7] In 2003, many nanotech companies were a little tired of answering questionnaires on the economic potential of nanotechnology as a number of commercial organisations had already carried out ‘quick and dirty’ surveys on the subject.

Nanotechnological products	**Annual world market volume (reference year)**
Chemistry	
Nanomaterials	
metal oxide/metal nanoparticles	900 million USD (2005) [27]
nansilicic acid	800 million EUR (2003) [39,40]
nanolayer silicates	25 million USD (2006) [41]
carbon nanotubes	145 million USD (2005) [30] 1.2 billion USD (2006) [26]
carbon black	3 billion USD (2002) [42] - 8 billion USD (2006) [26]
polymer dispersions	15 billion EUR (2002) [25]
organic semiconductors	500 million. USD (2005) [43]
dendrimers	5-15 million EUR (2006) [41]
micronized active substances	1 billion EUR (2002) [25]
zeolites	2.6 billion USD (2006) [26]
aerogels	10 billion USD (2005) [44]
polymer nanocomposites	0.3 billion USD (2006) [40] - 1.5 billion EUR (2009) [43]
Intermediate products	
corrosion protection paper	10-50 million EUR (2006) [1]
varnishes	50-250 million EUR (2006) [1]
films for displays	50-250 million EUR (2006) [1]
marker substances	250-500 million EUR (2006) [1]
Nanosensors	
temperature sensors	4.6 million USD (2004) - 217 million USD (2011) [43]
pressure sensors	4.4 million USD (2004) 87 million USD (2011) [43]
chemical sensors	1.3 million USD (2007) - 36 million USD (2011) [43]
Nanotechnological products	Annual world market volume (reference year)
Car manufacture	
magnetoelectronic sensors	600 million USD (2006) [1]
antifog-coatings for headlights	50-250 million EUR (2003) [1]
varnishes	50-250 million EUR (2006) [1]
car tires	7 billion EUR (2006) [1]
components with hard coatings	0.5-1 billion EUR (2006) [1]
Electronics	
CMOS-electronics <100 nm	20 billion USD (2006) [1]
GMR-HDD	26.6 billion USD (2006) [26]
MRAM	30-50 billion USD (2010) [46], (DRAM-replacement)
Optical industry	
ultraprecision optics, thereof lithography optics	1-5 billion EUR (2006) [1] 0.5-1 billion EUR (2006) [1]

Fig. 3. Assessments of the annual world market volume of nanotechnological products in the respective lead markets [39–47].

lithography-steppers	7.7 billion USD (2006) [26]
LED, thereof white LED	1-5 billion EUR (2006) [1] - 10-50 million EUR (2006) [1]
Diode lasers, thereof high-efficiency diode lasers	1-5 billion EUR (2006) [1] 50-250 million EUR (2006) [1]
OLED-displays	0.1 billion USD (2002) - 2.5 billion USD (2006) [19]
CNT-FED	0.01 billion USD (2002) - 0.05 billion USD (2006) [26]
optical sensor technology	1-5 billion EUR (2006) [1]
laser interferometer	10-50 million EUR (2006) [1]
optical thin-film measurement technology	250-500 million EUR (2006) [1]
Life Sciences	
Medicine/pharmacy	
biophysical analytics	181 million USD (2002) - 745 million USD (2007) [45]
total market biochips/quick tests	2 billion USD (2010) [47]
DNA-chips	1.9 billion USD (2006) [26]
protein chips	0.4 billion USD (2006) [26]
nanobased diagnostics and analytics	80 million USD (2002) - 391 million USD (2007) [45]
active substances and drug delivery	8 million USD (2002) - 33 million USD (2007) [45]
tissue engineering	0 million USD (2002) - 1.5 million USD (2007) [45]
Ag-nanoparticles in antimicrobics	1 million USD (2005) [27]
Cosmetics	
nanoparticles in sun protection products	86.5 million USD (2005) [27]

Fig. 3 (*continued*).

companies see Japan and the rest of Asia as competitors in the diffusion of nanotechnology. This result is partly confirmed by the analysis of the evaluation of the strength of potential competitors and R&D and its realization on the market. As regards R&D, it appears that Asia and Europe lag behind the USA and Germany. However, *as regards the transformation of nanotechnology into products, the interviewees said that the USA and Japan have performed better than Germany.*

The majority of the companies assessed the prospects of nanotechnology as positive. About 90% of the companies polled intended to enhance their activities in nanotechnology, 30% of them even considerably. This was also accompanied by an increase in employment. Only 18% of the companies interviewed did not see growing manpower requirements for their nanotechnological activities. German nanotechnology companies have been concentrating predominantly on research, a fact that can be deduced from the priority given to the provision of research personnel, contacts with cooperation partners and real investment activities. Thirty-four companies of the sample were large-scale enterprises and 72 companies were SMEs. A significant difference could be seen in the funding sources. The SMEs believed that they had significantly poorer access to the capital market than large-scale enterprises and that their access to market information was more complicated.

8. Collective debate on desk research and business survey findings

8.1. Research method: branch-specific expert workshops

All results of the literature review, patent analysis and the business survey (*traditional market research module*) were presented at 4 expert workshops in the form of theses to prompt constructive dialogue. The Delphi method – very popular in foresight – was the key methodological element and was used integrating the *traditional market research module* (literature review, patent analysis, the exploratory expert interviews and the business survey) and the *foresight module* (stakeholder dialogue in workshops, SWOT analysis). Background information was transformed into Delphi statements, making them accessible for future-oriented collective reasoning. In the 4 workshops, 15 to 25 experts took part. They came from banks, science, competence centres for nanotechnology, producers, suppliers, system developers and venture capital companies, and dealt with one or another chosen branches. In theory, the choice of experts could have been a problem, due to the use of the Delphi method. These experts could have tried to position their special subject areas in a particular way [38]. However, steps were taken to avoid this problem, by involving a large number of experts from the different fields of operation and ensuring an adequate balance between these fields.

The first step was to question experts from the chosen lead markets about the topics "nanotechnological product/market potentials along the value-added chain", "innovation/implementation obstacles" and "patents". The experts were asked to analyze the results and theses and say how realistic they thought they were. In a second step, they were presented with some of the more topical *societal expectations on nanotechnology* — for instance, the impact of uncontrolled release of nanoparticles and the demand by some social interest groups for a moratorium on development in order to raise awareness among scientists and industrialists of possible societal expectations (hopes and fears).

8.2. Research findings

The market potential of nanotechnological applications in the major German markets are summarized in Fig. 3. *It is not possible to deduce the nanotechnological world market* from this because:

- market information is only available for some nanotechnological products and lists are therefore incomplete;
- market forecasts can refer to different time horizons;
- double references to nanotechnological products in two or more sections occur (e.g. application of nano-basic-products/components in products of other fields);
- the survey includes products from different stages of the value-added chain (basic products, intermediate products, end products etc.).

Concerning the societal expectations on nanotechnology, it was recommended by industrialists and scientists participating in the workshops that more research should be done on the reaction of the organism to nanoparticles — for example, if they are ingested by breathing or through the skin. The experts believed that lack of information, awkward communication and insufficient knowledge of the facts could lead to poor acceptance of emerging technologies, not least nanotechnology, and become a considerable innovation obstacle. In order to avoid such *innovation obstacles* and mistakes, nanotechnology-related *research activities in the fields of toxicology, environmental studies and ethics* like in the USA (NSF), United Kingdom (Royal Society) and Germany (as BMBF and TAB) were suggested.

9. SWOT analysis

9.1. Research method: Strengths and Weaknesses and Opportunities and Threats analysis

By the year 2015, it is expected that almost all fields of industry will be affected by nanotechnology. The fields that will be most influenced by nanotechnology are chemistry, life sciences and electronics. Based on the information gathered by means of another structured method (SWOT analysis) which can be seen as the *second element of the foresight module*, a further analysis of the status of nanotechnology in Germany and the existing chances and deficits was carried out. This SWOT analysis, done by the participants of the 4 Delphi workshops comprises a Strength–Weakness-analysis, i.e. the evaluations of the factors are influenced by stakeholders in Germany, and an Opportunities–Threats-analysis, i.e. an assessment of the global factors. It comprises an analysis of strengths und weaknesses of factors that may influence Germany, and an analysis of global opportunities and threats.

Strengths	**Weaknesses**
• There is a high proportion of German small-sized enterprises active in nanotechnology • Germany disposes of a pronounced strength in the fields of chemistry/materials in nanotechnology • In international comparison Germany shows a considerable strength in nanotechnological research	• The number of medium-sized companies active in nanotechnology is relatively low • Partly weak commitment of traditionally strong industrial fields (e.g. mechanical engineering) to nanotechnology
Opportunities	**Threats**
• Intensified commercial realization of partly excellent results of research is required	• Financing of activities in nanotechnology is regarded as one of the greatest challenges (and innovation barriers) • Suitably qualified staff and adequate partners for cooperation are also considered to be a challenge

Fig. 4. SWOT analysis of nanotechnology in Germany.

9.2. Research findings

The SWOT analysis set out in Fig. 4 gives examples of dominant Strengths and Weaknesses of nanotechnology in Germany. The SWOT analysis confirms the most striking statements of the paper-based business survey and their assessment by the experts participating in the 4 branch-specific workshops. Financing of nanotechnology companies was categorized as a "Threat". Because of the reluctance of venture capitalists to invest in start-up companies, it was seen as a major problem. However, the summary revealed that, overall, Germany has an excellent starting position for the economic realization of activities in nanotechnology. The excellence of research, however, is not reflected completely in commercialization. Here, the USA and Japan are a long way ahead of Germany. It must also be taken into account that investments and public funding in the field of nanotechnology have increased considerably worldwide, a fact partly attributable to the very high market volumes forecasted. In the future, stronger international competition in nanotechnology can be expected, and players from outside the USA, Japan and Germany will become more prominent.

10. Concluding remarks

One major goal of study we discussed in this article was to assess realistically the market volume and relevance of nanotechnology. Another main goal of this study was to bridge the gap between foresight and traditional market research, while doing empirical research on the economic potential of a specific emerging technology and applying methods popular in traditional market research and foresight. With regard to the acquisition and analysis of data in the field of nanotechnology, *integrating the traditional market research module and the foresight module proved valuable*, providing qualitative (exploratory expert interviews, literature review, branch-specific expert workshops, SWOT analysis) and quantitative (paper-based business survey and patent analysis) methods for the determination of economic potential. The 4 branch-specific Delphi workshops were particularly useful as they allowed (provisional) results to be critically examined and evaluated by acknowledged experts from industry, science and finance in a broader societal context. In this way, elements of participative foresight and technology assessment processes were also brought into the study, as the basis for constructive discussion with the relevant stakeholders.

It has to be stressed that it was not a full foresight exercise since societal stakeholders like consumers or environmentalists were not involved and no work was done on alternative futures. Nevertheless, the chosen approach adopted a component of collective anticipatory intelligence through stakeholder dialogue. *The key methodological innovation for this was to translate desk research and business survey findings into Delphi statements and to use Delphi methods to structure the dialogue* (not as prediction). This was successful as the results are now much more coherent, and also other aspects like societal expectations were addressed. It would otherwise have been difficult to find out that it does not make sense to deduce the "nanotechnological world market" from the results, or that industry is well aware of nanotechnology's environmental and ethical issues and is very interested in broader stakeholder dialogues and further research on these issues. Compared to long-term foresight much more concrete information on economic potential was generated. In the future, similar applications of such *market foresight modules* may be useful as elements of foresight and also in cases of emerging technologies, like converging technologies, cognitive science and Web 2.0, where pure market research does not produce a realistic market assessment [7,48,49]. However, *the solution proposed in the article demands as managerial* *implications interdisciplinary team work consisting of economists and natural and social scientists, solid financial resources for the project, and the dedication of more time (18–24 months) than traditional market research*, if the gap between foresight and traditional market research is to be bridged.

References

[1] N. Malanowski, T. Heimer, W. Luther, M. Werner, Growth Market Nanotechnology: An Analysis of Technology and Innovation, Wiley-VCH, Weinheim, 2006.
[2] http://forlearn.jrc.es/guide/1_why-foresight/characteristics.htm, visited on February 2, 2007.
[3] A. Webster, Foresight as a tool for the management of knowledge flows, Proceedings of STRATA consolidation Workshop, Session 5, Brussels 22 & 23 April 2002.
[4] A. Salo, K. Cuhls, Technology foresight — past and future, J. Forecast. 22 (2/3) (2003) 79–82.
[5] B. Martin, R. Johnston, Technology foresight for wiring up the national innovation system. Experiences in Britain, Australia, and New Zealand, Technol. Forecast. Soc. Change 60 (2) (1999) 37–54.
[6] L. Georghiou, Third generation foresight – integrating the socio-economic dimension, technology foresight – the approach to and potential for new technology foresight, Proceedings of the International Conference on Technology Foresight, NISTEP Research Material, Tokyo, March 2001.
[7] E.A. Eriksson, K.M. Weber, Adaptive foresight: navigating the complex landscape of policy strategies, Paper Prepared for the Second International Seville Conference on Future-Oriented Technology Analysis, Sevilla, 28–29 September 2006.
[8] R.E. Davis, The role of market research in the development of new market products, J. Prod. Innov. Manag. 10 (3) (1993) 309–317.
[9] J.W. Mullins, New product development in rapidly changing markets, J. Prod. Innov. Manag. 15 (2) (1998) 224–236.
[10] Bundesministerium für Bildung und Forschung (BMBF), Nanotechnologie erobert Märkte- Deutsche Zukunftsoffensive für Nanotechnologie, BMBF, Bonn, 2004.
[11] A. Zweck, Three perspectives for one future in economy and society, Futures Res. Q. 18 (1) (2002) 22–33.
[12] http://www.nanologue.net/index.php?seite=142&PHPSESSID=65c22c6472f3fab4f81ba97f780f6e8d, visited on February 2, 2007.
[13] Evolution Capital Limited: Nanotechnology, Commercial Opportunity, ECL, London, 2001.
[14] M. Beckmann, P. Lenz, Profitieren von Nanotechnologie: Investment der Zukunft, Verlag Vahlen, Munich, 2002.
[15] TAB, TA-Projekt Nanotechnologie, Arbeitsbericht Nr. 92, TAB Büro für Technikfolgen-Abschätzung beim Deutschen Bundestag, Berlin, 2003.
[16] 3i, Nanotechnology — size matters, A 3i white paper in association with the Economist Intelligence Unit and the Institute of Nanotechnology, London, 2002.
[17] U.V. Alemann, Einführung in die Methoden der Politikwissenschaft, Westdeutscher Verlag, Opladen, 1995.
[18] H. Wollmann, Politikevaluierung, Evaluierungsforschung, in: D. Nohlen (Ed.), Kleines Lexikon der Politik, Piper Verlag, Munich, 2001.
[19] T. Heimer, M. Werner, Die Zukunft der Mikrosystemtechnik — Quo vadis MST? Ergebnisse der ex-ante Evaluation des Förderkonzepts Mikrosystemtechnik 2000+, Wiley-VCH, Weinheim, 2004.
[20] OECD, Biotechnology Statistics, Paris, 2006.
[21] U.S. Department of Energy, Carbon Sequestration, U.S. Department of Energy, Washington D.C., 1999
[22] K. Blind, K. Cuhls, H. Grupp, Personal attitudes in the assessment of the future of science and technology: a factor analysis approach, Technol. Forecast. Soc. Change 68 (2) (2001) 131–149.
[23] M.N. Rittner, Market analysis of nanostructured materials, Am. Ceram. Soc. Bull. 81 (3) (2002) 822–834.
[24] M.C. Roco, The vision and action plan of the National Nanotechnology Initiative, http://www.cr.org/publications/MSM, visited on March 3, 2003.
[25] BASF/Distler, Nanoteilchen in Megatonnen, Vielfältige Anwendungen für Polymerdispersionen, BASF press release, May 2002.
[26] H.J. Fecht, J. Ilgner, T. Köhler, S. Mietke, M. Werner, Nanotechnology market and company report — finding hidden pearls, WMtech Center of Excellence Micro and Nanomaterials, University of Ulm, 2003.

[27] BCC: global nanotechnology market to reach $29 billion by 2008, press release from 03.02.2004, Business Communication Company, http://www.bccresearch.com/editors/RGB-290.html, visited on March 7, 2004.
[28] G. Bachmann, Innovationsschub aus dem Nanokosmos — Technologieanalyse, VDI Technology Center, Future Technologies, vol. 28, VDI Technology Center, Düsseldorf, 2001.
[29] M. Rödiger, P. Fuchs, H. Müller, Zukünftiger Wachstumsmotor in der Chemieindustrie, Im Fokus Nanotechnologie in der Chemie, 2001, Frankfurt a. M.
[30] Mitsubishi Research Institute: promoting Japanese-style nanotechnology enterprises, Presentation of S. Kamei at the 1st. Jetro International Nanotechnology Symposium on February 26, 2002 in Chicago, USA.
[31] P. Jankowski, Mikrosystemtechnik und Nanotechnologie — Schlüsseltechnologien für Deutschland, Sal. Oppenheim, Cologne, 2001.
[32] D. Normile, Court tells Nichia to Pay Blue LED Inventor 180 Million USD, Science, vol. 303(1), 2004, p. 47.
[33] A.J. Wurzer, Patentbewertung-Technologische und wirtschaftliche Aspekte, workshop discussion of the Zentrum für Gewerblichen Rechtsschutz of the University of Düsseldorf, http://www.gewrs.de/files/wg_2002_0415_patentbewertung.pdf, visited on December 12, 2002.
[34] R. Pitkethly, The Valuation of Patents, Background Article for the First Meeting of the High Level Task Force on Valuation and Capitalization of Intellectual Assets, European Commission, Brussels, 2002.
[35] T. Braun, A. Schubert, S. Zsindely, Nanoscience and nanotechnology on the balance, Scientometrics 38 (2) (1997) 84–97.
[36] R. Compano, A. Hullmann, Forecasting the development of nanotechnology with the help of science and technology indicators, Nanotechnology 13 (2) (2002) 67–79.
[37] J. Johnson, R. Joslyn, Political Science Research Methods, CQ Press, Washington D.C., 1991.
[38] G. Tichy, The over optimism among experts in assessment and foresight, Technol. Forecast. Soc. Change 71 (4) (2004) 341–363.
[39] M. Meyer, O. Persson, Y. Power, (Nanotechnology Expert Group and Eurotech Data), Mapping excellence in nanotechnology, preparatory study, http://europa.eu.int/comm/research/era/mapping-excellence.html, visited on February 12, 2002.
[40] Wacker Silicones, News, www.wacker.com, 2003, visited on October 3, 2003.
[41] SRI, Nanoscale chemicals and materials: an overview on technology, products and applications, SRI-International Report, Speciality Chemicals: Nanotechnology, Arlington, 2002.
[42] Reuters, Degussa investigations into alleged price-fixing in the carbon black industry, press release, September 17, 2002.
[43] R. Stevenson, OLEDs Set to Glow, e-zine chemSoc., 2003 www.chemsoc.org/chembytes/ezine/2003/stevenson_jan03.htm visited on October 12, 2003.
[44] Aspen Systems: Aspen Systems takes a giant step toward commercialization of Aerogels, press release, April 23, 2001.
[45] BCC, Biomedical applications of nanoscale devices: commercial opportunities, Conference Proceedings, Nanotech and Biotech Convergence, BCC, Stanford, 2003.
[46] Small Times, Veeco Came, Saw, Acquired Majority of the AFM Market, 2002 www.smalltimes.com visited on March 3, 2003.
[47] VDI-News, Issue from March 28, 2003, 5.
[48] M. Rader, A.L. Porter, FTA assumptions: methods and approaches in the context of achieving outcomes, Paper Prepared for the Second International Seville Conference on Future-Oriented Technology Analysis, Sevilla, 28–29 September, 2006.
[49] K. Blind, Regulatory foresight: methodologies and selected applications, Paper Prepared for the Second International Seville Conference on Future-Oriented Technology Analysis, Sevilla, 28–29 September, 2006.

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