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Measuring and assessing the development of nanotechnology*

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Nanotechnology merits having a major impact on the world economy because its applications will be used in virtually all sectors. Scientists, researchers, managers, investors and policy makers worldwide acknowledge this huge potential and have started the nano-race. The purpose of this paper is to analyse the state of the art of nanotechnology from an economic perspective, by presenting data on markets, funding, companies, patents and publications. It will also raise the question of how much of the nano-hype is founded on economic data and how much is based on wishful thinking. It focuses on a comparison between world regions, thereby concentrating on Europe and the European Union in relation to their main competitors – the United States and Japan and the emerging 'nano-powers' China and Russia.

Introduction

Nanotechnology can be everywhere. It is in car tyres, in tooth paste, in sun cream, in tennis rackets and tennis balls, in shirts and trousers, in CD players and even in surfaces

* The views expressed in this document are entirely those of the author and do not necessarily represent the official position of the European Commission. For more information on nanotechnology at the European Commission, please visit http://cordis.europa.eu/nanotechnology

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of bath tubes, toilets and wash basins. With new properties such as smaller, lighter, faster, cheaper, water, dirt and stain resistance which enhance consumer goods. Are these products signs for the takeoff into the nanofuture, as many experts foretell? Are they first steps towards 'nanorobots' and 'matter compilers', towards a world with eternal life and inexhaustible resources?

Nowadays it is widely accepted that nanotechnology is a collection of different technologies and approaches, which all use the physical properties of dimensions on the nanometre scale, which differ from those observed in the micro and macro world. In order to draw a correct and comprehensive picture of the technology and to achieve a fair assessment of its status, potentials and drawbacks, it is necessary – where possible – to look at nanotechnology subareas such as nanomaterials and nanoelectronics, nanobiotechnology and nanomedicine, or nanotools, nanoinstruments and nanodevices.

Nanomaterials are expected to have the major influence on virtually all fields where materials play a role. They include ultra-thin coatings and active surfaces as well as the new generation of chemical engineering. Nanoelectronics has a major impact on the information and communication technologies by continuing or overcoming (with the help of quantum electronics) Moore's law of doubling data storage and processing capacities every 18 months. Nanobiotechnology will make the difference in medicine, for pharmaceuticals and diagnostics, in countless industrial processes, agriculture and food industry. Nanotools are nanotech enabling technologies, such as electron microscopes (Scanning Tunnel Microscope STM, Atomic Force Microscope AFM) and ultra-precision machines.

In this article, the state of the art of nanotechnology will be analysed by presenting available data on nanotechnology markets and market projections, on jobs, on companies and other organisations active in nanotechnology, on public and private funding, including Venture Capital funding, on patents, and on scientific publications. The data have been collected from publicly available sources and will be cited accordingly. The author cannot take the full responsibility for their accuracy or trueness. Especially in the case of market data, which can only be estimates, the data differ very much depending on definition, source, methodology and purpose of collection and presentation. The author sought to overcome this problem by not relying on a single source and by comparing different sources before selecting them for further analyses.

The purpose of the analyses is twofold: On the one hand, nanotechnology and its subareas will be analysed in order to present the state of the art, to identify most promising fields and to predict future developments. On the other hand, the analyses will shed a light on the contribution of nanotechnology to economic and social goals of the European Union such as competitiveness, economic growth and employment by focusing on Europe in comparison with its world competitors, mainly the United States, Japan and emerging nano-powers such as China, India and Russia.

Commercialisation of nanotechnology: prospects of market volumes and shares

Because nanotechnology is expected to have a substantial impact on the world's economy, the market volume is an appropriate indicator for its economic significance. On the other hand, nanotechnology does not correspond to an industry that can easily be identified and quantified. Nanotechnology will, if successful, contribute substantially but not in an easily quantifiable way to many product improvements and allow the production of completely new products.

Most market forecasts for nanotechnology originate from the early 2000s, with a time horizon up to 2015. The maybe best known figure for the future nanotechnology market has been published by the National Science Foundation (NSF) of the United States in 2001. The NSF estimated a world market for nanotechnological products of 1 trillion US Dollars for 2015. Depending on the definition of nanotechnology and its contribution to added value of the final products as well as the degree of optimism, many other forecasts vary between moderate 150 billion in 2010 (MITSUBISHI INSTITUTE, 2002) and 2.6 trillion in 2014 (LUX RESEARCH, 2004). The latter, most optimistic scenario would imply that the market for nanotechnology-based products would be larger than the prospective information and communication technology market and would exceed the future biotech market by ten times.

Figure 1 shows some forecasts from different sources. The forecasts differ significantly from each other, but have somehow in common that they predict a substantial increase of the market for nanotechnological products with a take off somewhere in the early 2010s.

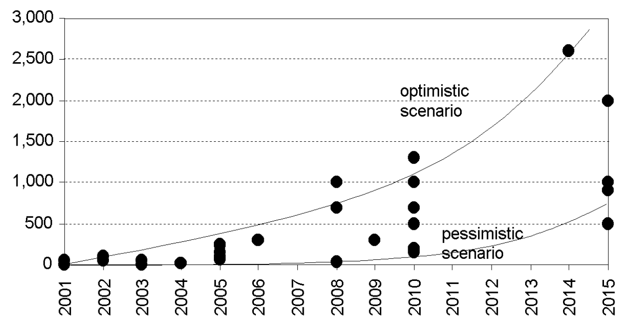

Figure 1. World market forecasts for nanotechnology in billion US Dollar. Diverse sources

The figures presented above show the possible direction, but are not adequate for deeper analyses of the development of the nanotechnology market. Lux Research and the NSF have both spent some efforts in breaking the figures down in nanotechnology subfields. The analyses show that in the today's (1999–2003) market for nanotechnology products, nanodevices and nanobiotechnology are estimated to be responsible for the largest shares of around 420 and 415 million US Dollar. Materials and tools play a minor role with 145 and 50 million US Dollar. In the forecasts by NSF for 2015, all areas are expected to undergo significant increases, e.g. for materials from 145 million up to 340 billion US Dollar. Nanoelectronics will amount to 300 billion US Dollars, followed by pharmaceuticals, chemical processing and aerospace.

However, any comparisons of actual numbers and forecasts from different sources and with different breakdowns have to be interpreted carefully. Many other studies have tried to prospect the nanotechnology market. All data differ, depending on the study and the point of reference, even sometimes significantly for the same year. In a compilation of different nanotechnological subareas, applications and markets, nano-enabled products are expected to be responsible for the largest share. The estimates for the whole area of nanoelectronics are around 300 billion for 2015, which covers semiconductors, ultra capacitors, nanostorage and nanosensors. The market for nanomaterials estimates can be broken down to some more or less important subareas, amongst which nanoparticles, nanocoatings and lateral nanostructures account for more than 300 billion Euro in all materials around 2010. These figures come very close to the NSF estimate for 340 billion US Dollar in 2015. The data – though fragmented and partially not comparable – lead to the assumption that nanomaterials will give a great contribution to future markets and applications. One could conclude that the moderate increases up to 2006 will be topped by much stronger dynamics at some time between 2006 and 2010, depending on the material area.

The three phases model of LUX RESEARCH (2004) shows the so far most comprehensive and sophisticated prospect of the developments in the nanotechnology market. The model includes a first phase up to 2004 with some nanotechnology incorporated in high-tech products. The next phase up to 2009 will bring breakthroughs for nanotechnology innovations. Nanoelectronics would dominate this market. In a third phase from 2010 onwards, nanotechnology will become commonplace in manufactured goods with healthcare and life science applications entering the pharmaceutical and medical devices markets. Nanobiotechnologies will contribute significantly to the developments in the pharmaceutical industry. Basic nanomaterials as such will loose importance at this time. LUX RESEARCH (2004) estimates a market share for nanotechnology products of 4% of general manufactured products in 2014, with 100% nanotech in PCs, 85% in consumer electronics, 23% in pharmaceuticals and 21% in automobiles. This would lead for nanotechnology to an overall share of 15% of the global manufacturing output in 2014.

None of the above presented projections include ranges of scenarios that are related to the public acceptance of nanotechnology, though lessons should be learnt from former emerging technologies such as nuclear power technology or Genetically Modified Organisms (GMO). Experience shows that citizens' expectations and concerns as well as perceptions of risks and benefits have to be taken into account, since they present an important impact on the acceptance of new technologies on the market and can decide market success or failure. The ongoing debates on nanotechnology show that some controversies exist and that market success could be jeopardised if public opinion feels that it is not being addressed and consequently takes over a critical view about nanotechnology as such due, e.g., to health and environmental risks of nanoparticles or ethical concerns about privacy. When talking about economic potentials of nanotechnology, these debates have always to be addressed and must be taken seriously.[1]

These aspects can also have a substantial impact on the global distribution of sales and economic returns of nanotechnology products. While some world regions might be more inclined to accept the risks related to nanotechnology, even if they are not fully known or quantified yet, others can be more critical and more reluctant in their acceptance. The difference between the acceptance of genetically modified crops between the European and the American public illustrates this case adequately. Stricter regulations and less explicit marketing of the nanotech element in the products can be the consequence for the more critical regions.

LUX RESEARCH (2004) has broken down the figures of their forecasts (2.6 bn in 2014) by region. Most interestingly, the most important region for the sales of nanotechnology products is Asia and the Pacific region, followed by the USA and Europe on similar levels. While Europe is predicted to have a small but continuous increase of its share, the US is decreasing until 2008 and increasing afterwards, Asia and the Pacific undergo the opposite development. The reasons Lux Research gives for these developments are related to the three-phase model of the nanotechnological development: in the nearest future, products will dominate the world market that primarily originate from strong Asian companies, such as PCs, mobile devices or vehicles. After 2008, pharmaceuticals will become stronger and these are dominated by US companies.

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[1] In the communications *Towards a European Strategy for Nanotechnology* (2004) and *Nanosciences and Nanotechnologies: An action plan for Europe for 2005 to 2009* (2005), the European Commission highlighted the importance of an integrated and responsible approach towards nanotechnology, by identifying not only scientific, technological and economic conditions as being important for the further development of nanotechnology, but also the societal dimension, risk assessment and an international dialogue. See on http://cordis.europa.eu/nanotechnology/actionplan.htm

The global nano-race: some data on public and private funding

The National Nanotechnology Initiative (NNI) in the United States, launched by the former president Clinton and entering into force in 2001, can be seen as the starting point of a global race for the world leading economies in nanotechnology research programmes. However, funding for nanoscience was already established in many regions of the world by this time, with Europe already being strong in nanomaterials by the mid-1980s. Up to now, many other countries and the European Union have dedicated considerable amounts of money to nanotechnology research and development. Table 1 gives a snap shot of public funding activities in 2005.

The European Commission is the largest funding organisation of nanotechnology research in Europe and as an individual agency even worldwide. In the 6th European Framework Programme for Research and Technological Development (FP6), nanotechnology has been defined, together with materials and production technologies (NMP), as a priority for European research. It is estimated that 1.3 billion Euro have been dedicated to nanotechnology projects between 2004 and 2006 (2004: 370 million Euro, 2005: 470 million Euro, 2006: 500 million Euro), also in other priorities than NMP such as the information society technologies, infrastructures, or research and training activities. Already within FP4 and FP5, from 1994 to 2002, nanotechnology related projects were funded which amounted to 300 million Euro in total. In the upcoming FP7 (2007–2013, for more information see http://cordis.europa.eu/fp7), nanotechnology will continue as a priority within the NMP theme and is expected to at least double the budget, with additional cross cutting activities related to the other FP7 themes (health, food, information & communication technologies, energy, socio-economic research and security) or programmes (infrastructures, SMEs, training, societal aspects). In addition, some emphasis will be put on nanoelectronics and nanomedicine as topics of European Technology Platforms and on safety, environmental and health aspects, nanometrology, converging technologies and international cooperation.

Regarding the EU Member States, which are accounting together for a much larger share of European public expenditure in nanotechnology than the European Commission, Germany is the top spender, followed by France and the UK. Japan and South Korea are on a comparable level. In addition, taking into consideration that the figures are not reflected in purchase power parities, China’s efforts must be considered as substantial and more than significant in a worldwide comparison. All countries are outdone by the United States, which is with the total expenditures of more than 1.2 billion Euros in 2004 and 1.7 billion Euros in 2005 by the federal government agencies and the federal states the largest public spending country worldwide. However, as a whole, and only taking into account the public funding of nanotechnology, Europe would be on a similar level as the United States (Figure 2).

Table 1. Estimated worldwide public funding, in 1000€,
for nanotechnology R&D in 2004 by individual countries

Country	Public funding (1000€)
USA (Federal)	910,000
Japan	750,000
European Commission	370,000
USA (States)	333,300
Germany	293,100
France	223,900
South Korea	173,300
United Kingdom	133,000
China	83,300
Taiwan	75,900
Australia	62,000
Belgium*	60,000
Italy*	60,000
Israel	46,000
Netherlands	42,300
Canada	37,900
Ireland	33,000
Switzerland	18,500
Indonesia	16,700
Sweden	15,000
Finland	14,500
Austria	13,100
Spain	12,500
Mexico	10,000
New Zealand	9,200
Denmark	8,600
Singapore	8,400
Norway	7,000
Brazil	5,800
Thailand	4,200
India	3,800
Malaysia	3,800
Romania	3,100
South Africa	1,900
Greece*	1,200
Poland*	1,000
Lithuania	1,000
Other	2,800
Total	3,850,000

* Data are from 2003.
Source: EUROPEAN COMMISSION (2005).

Adding the private funding figures, the picture looks different: In Europe, only one third of the total funding stem from private sources. In the United States, the private sources are around 60% and in Japan they account for more than two thirds. For all other, mainly emerging Asian countries, the share is slightly above 40%. In absolute numbers, the US research community can spend almost 3 billion Euros for nanotechnology, while it is 2.3 billion in Japan and less than 2 billion in Europe.

This shows the difference between Europe and its competitors in nanotechnological research. The public funding level is competitive, but European industry is lagging behind.

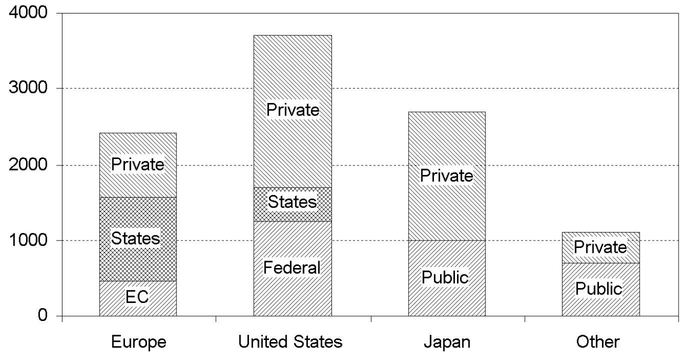

Figure 2. Estimated public and private funding for nanotechnology R&D in 2005
by world regions in million €
Source: EUROPEAN COMMISSION (2005), updated figures

Risk capital for high-tech research: venture capital funding of nanotechnology

Which areas of nanotechnology are already especially dynamic and thus attractive for investors? A closer look at the risk capital market up to 2002 gives an indication (PAULL et al., 2003). Nanobiotechnology as the most attractive market for Venture Capitalists, followed by nanodevices, while nanomaterials and nanotools play only a marginal role. The overall development Venture Capital (VC) world market for nanotechnology is presented in Figure 3.

The figures show a stagnation of the total VC funding development in 2002 and a moderate but steady increase afterwards. The share of nanotechnology in the world market of VC funding undergoes a similar development. This decrease can be explained by the fact that Venture Capitalists consolidated their views on nanotechnology, especially in regard to the risk debates related to possible dangers. The discussions became more vivid in the early 2000s when first results of toxicity analyses that have been published show a certain potential hazard related to nanoparticles. They are still going on and some investors might prefer to wait for more clear indications of the outcomes.

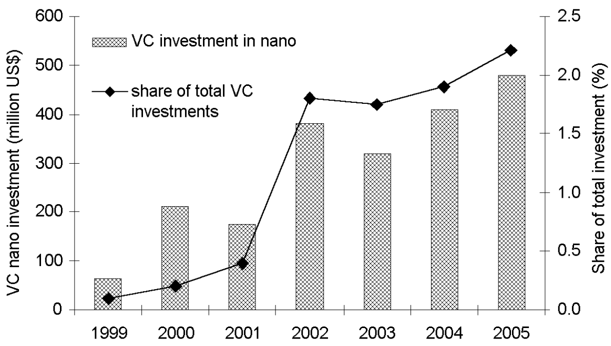

Figure 3. Venture Capital funding worldwide in nano, in absolute numbers and as share
Sources: 1999–2003: ANQUETIL (2005); 2004/2005: LUX RESEARCH (2006), PRICEWATERHOUSECOOPERS (2005)

On the other hand, some experts (NANOLOGUE, 2005) believe that a massive investment in nanotechnology could lead to products that society does not need. This lack of public involvement combined with huge investment and the hype surrounding nanotechnology would result in a "bubble" that could finally burst. In addition, the stagnation in 2002 and the decreasing growth afterwards might also be due to the fact that the market is already starting to get saturated. This is because demand for VC funding depends very much on the number of start up companies. Are there enough nanotechnological entrepreneurs who can absorb more than 500 million US Dollar annually or 2.2 percent of VC available world wide?

Analysing the economic impact: jobs and companies in nanotechnology

The creation of companies is an important indicator for the development and economic significance of a new technology. New companies are typically start ups with one main asset: the patent on a new technology which they can exploit themselves or license to other companies which are more capable in terms of production or distribution. Venture Capital is a major source of financing in this high tech and thus high risk sector.

When it comes to the creation of new jobs, start ups and small and medium-sized enterprises (SMEs) contribute most. The NSF estimates that about 2 million nanotechnology workers will be needed worldwide by 2015. They would be distributed across the world regions as follows: 0.8–0.9 million in the US, 0.5–0.6 million in Japan, 0.3–0.4 million in Europe, about 0.2 million in the Asia–Pacific region excluding Japan and 0.1 million in other regions. Additionally, 5 million related supporting jobs, or at average 2.5 jobs per nanotech worker, would be created (ROCO, 2003). Even more optimistic, LUX RESEARCH (2004) expects a number of 10 million manufacturing jobs related to nanotechnology by 2014. Figure 4 shows the total number of jobs in nanotechnology and its share of all manufacturing jobs.

Many of these jobs will be created in SMEs, but not exclusively. In the past few years, many already well established companies expanded their technology portfolio to nanotechnology in order to maintain their competitiveness. This explains why companies were identified as being nanotech oriented that sometimes even existed 100 years ago or even longer. Typical examples are big companies in chemical and pharmaceutical industry, optics and electronics (Bayer, BASF, Carl Zeiss, Agfa-Gevaert, General Electrics, Philips, all created before 1900), though these established companies form a minority in the list of all existing nanotech companies.

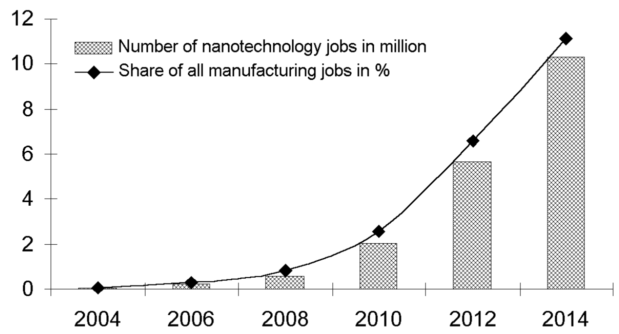

Figure 4. Number of nanotechnology jobs in million and the share of nanotechnology jobs of all manufacturing jobs in percent. Source: LUX RESEARCH (2004)

Figure 5 shows nanotechnology companies by their years of creation, worldwide and by world region. The data stem from the publicly available database of nanotech companies provided by NanoInvestorNews. For 522 companies out of the total of 1000 companies in this database the year of creation was provided. The world regions are composed mainly by Germany, Switzerland and the United Kingdom for Europe, the United States and Canada for the Americas and Japan, South Korea and China for Asia.

Only a few of the today's active nanotech companies had been created in the first eight decades of the 20th century, with an average of ten companies each decade. In the 1980s, the number increased significantly but the take off did not take place before 1996, in which about 30 nanotech companies were created – and up to 50 companies in

2000. This continues with increasing tendency, which is not reflected in the numbers due to incomplete data sets for the most recent years. It is important to note that all companies exist at the time of reference (May 2005), thus companies, which got bankrupt were acquired or got merged before, are not included in the statistics.

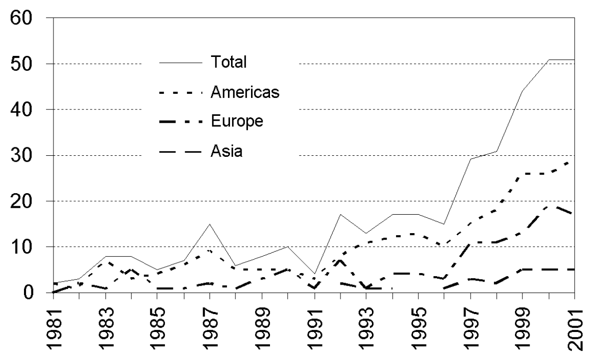

Figure 5. Nanotech companies worldwide: decades and years (1981–2005) of creation.
Note that some recently created companies (2001 or later) are not completely covered.
Source: NANOINVESTORNEWS database (as of 8th May 2005)

Is there any difference between the world regions for number and year of the creation of nanotech companies? The numbers up to the 1990s should not be overrated, because of statistical distortions due to small numbers. However, they reflect the same proportions between the word regions in a constant way: The Americas are in the lead, followed by Europe and Asia. In the late 1990s, Europe reduced the gap to the Americas from half to two thirds. The point of take off is for both, the Americas and Europe, in 1996, with a peak at 2000 for Europe and 2001 for the Americas for the present. It has to be noted that these figures of the today's state of the art cannot reveal the solidity of the companies regarded. Analyses of differences in the founding culture have that US companies are often less resilient compared to European companies and get bankrupted faster. This phenomenon is not examined here for companies active in nanotechnology.

In which nanotechnology segments are nanotech companies active? A survey by FECHT et al. (2003) covers 357 companies worldwide and shows that one third of the companies observed are active in nanomaterials, another third in nanobiotechnology. Nanotools and nanodevices play a smaller role. But there are significant differences between the four most active countries in the world: while the United States are pretty much average, Germany is stronger in nanotools, the United Kingdom in nanobiotechnology and Japan equally strong in nanomaterials and nanotools, above average in nanodevices and very weak in nanobiotechnology. The observed companies are mainly located the United States or Germany and to a lesser extent in the United Kingdom, Japan, Israel, Switzerland, Canada, and Sweden. (A similar ranking can also be observed in the dataset of NanoInvestorNews (see Figure 5, for which the figures are not given here.) The majority of the companies in the United States for which data are available are of medium size, i.e. 10 to 500 million US Dollar turnover. The majority of the German and the UK companies are much smaller with a turnover of below 10 million US Dollar, while the peak for Japanese companies can be found at 500 million US Dollar or higher.

Private companies are not the only organisations active in nanotechnology. The number of all organisations that do research or produce nanotechnology reflects all nanotechnology R&D activities and helps to identify patterns of activity in terms of scientific and applied research. CIENTIFICA (2003) has broken down the number of organisations active in nanotechnology to institutional type, to most active countries and to world region. The dataset comprises around 1100 organisations, of which 460 are SMEs or start-ups, 390 research institutes, 120 large companies and 80 subsidiaries or joint ventures. But there are differences between the world regions: While SMEs and start ups have the by far largest share in the United States, universities and research centres play a bigger role in Europe and Asia. Grouped together in two groups – all companies (including SMEs, big companies and subsidiaries) on the one side and research institutes (universities and research centres) on the other side –, interesting differences between the countries can be observed. The share of research institutes of all organisations is very high in Japan, the United Kingdom, China, France, Australia and Sweden. In Austria, Spain, Italy and Poland, they even outnumber the companies. The proportion is different in the United States, Germany, Switzerland, Israel and Taiwan as well as in South Korea and Finland, where the number of companies doubles or more the research institutes.

Another nanotechnology database focuses on European countries and shows the entries onwww.nanoforum.org. Nanoforum is a European internet gateway for nanotechnology, financed by the European Commission. In August 2005, 1538 organisations were registered in this database, from 33 European countries. Though half of the entries stem from Germany, this database shows also the activity of smaller and less active countries in nanotechnology. France and the United Kingdom are in the same level with together 250 entries, followed with a larger gap by the Netherlands, Austria, Switzerland and Belgium. Italy leads the midfield that includes Czech Republic, Denmark, Poland, Hungary, Sweden, Iceland, Israel, Lithuania, Slovakia and Slovenia.

From the data presented in this section, one can conclude that the most significant developments in the creation and activity of nanotech companies and nanotech related jobs can be observed in the United States. In Europe, Germany plays the most significant role, but on a rather moderate level when compared to the United States.

Japan is the United States' most important competitor. When it comes to competitiveness and job creation, the significance of companies being built on nanotechnological inventions or applying nanotechnology within their technological portfolio will increase.

The emerging nanotech countries China, India and Russia are prepared to take-off and to approach Europe. Although none of them appear prominently in the company statistics, it can be assumed that they will show significant dynamics in the next decades and can become serious competitors on the world market for products and for research and production sites. First evidence gives the indicators for scientific and technological development, which are analysed in the following chapters.

The technological development of nanotechnology: patent applications

Durable economic success would not be possible without a strong scientific and technological basis. On the other hand, scientific and technological excellence does not automatically facilitate economic success and breakthrough. The so called 'European paradox', which referred to Europe's strength in science and its weakness in technological application and consequently economic success, did reflect these causalities. Is there a European paradox for nanotechnology also? For approaching the answer to this question, it is advisable to have a closer look at the two main quantifiable indicators of scientific and technological excellence: patents and publications.

Patents reflect the ability of transferring scientific results into technological applications. Patents are also a prerequisite for economic exploitation of research results and are thus central for any analysis which deals with economic potentials of a technology and the identification of most promising fields and actors in terms of persons, organisations, or countries. The European Patent Office (EPO) has developed a methodology in order to identify and classify nanotechnology patents and patent families at most important patent offices worldwide.[2] The initial purpose was to facilitate the work of the patent examiners and to identify developments in this emerging field in order to respond upfront to increased need of new patent examiners and interdisciplinary cooperation. The introduced 'tagging' method also serves researchers who are interested in patent analyses in the field of nanotechnology. It has the clear advantage that nanotech patents can be identified more adequately and that

[2] For more information on rationales and methodology of the Y01N nano tag see SCHEU et al. (2006). The tags are as follows: Y01N= Nanotechnology, Y01N2 = Nanobiotechnology, Y01N4 = Nanotechnology for information processing, storage and transmission (short: Nanoelectronics), Y01N6 = Nanotechnology for materials and surface science (short: Nanomaterials), Y01N8 = Nanotechnology for interacting, sensing or actuating (short: Nanodevices), Y01N10 = Nanooptics, Y01N12 = Nanomagnetics.

worldwide comparisons are more reliable because no world region is favoured.[3] Figure 6 shows the evolution of the number of patent families from 1995 to 2003 and the break down to country of applicants, grouped by world regions, i.e. the Americas (mainly the US and Canada), Asia (mainly Japan and South Korea) and Europe (mainly Germany, the UK, France and the Netherlands).

The number of patent families increases continuously but with as yet no real take-off. Two small peaks in 1999 and in 2002 pointed to an exponential growth path, but in each case in the following year it had to suffer a slow-down which affects the overall growth rates in the period regarded. From which world regions do these nanotechnology patents stem? It is obvious that America is the by far most active world region for registering patents in nanotechnology. For each year in question they count for half of the patents for which the country of applicant could be identified. Interestingly, this leading position is slightly weaker when it comes to the country of inventor (not shown in Figure 6), where Asia improves its position

The growth of the number of nanotechnology patents is marked by larger increases in the late 1990s and smaller ones in the early 2000s. The development of the number of patents originating from the United States is very similar to the overall development of all nanotechnology patents. The opposite picture can be observed for all other countries: small increases or even decreases (France, the Netherlands) in the 1990s and significant growth in the years 2000. Germany, Canada, the UK and in particular the Netherlands and South Korea have shown a much more dynamic development in the last period regarded.

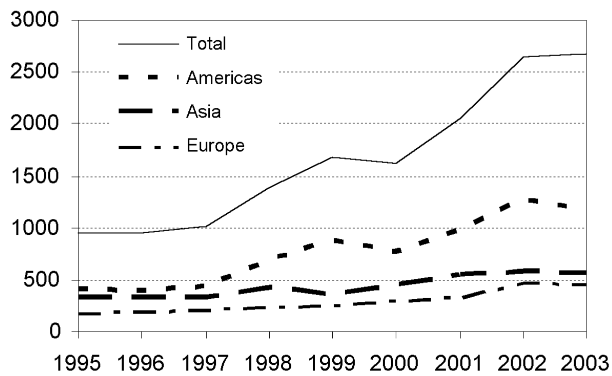

Figure 6. Nanotech patents worldwide according to EPO tag Y01N: distribution by regions, according to applicant country. Source: EPO (2006) and own calculations

[3] For a comparison of patent analyses by different authors, their methodologies and results, advantages and shortcomings, see HULLMANN & MEYER (2003).

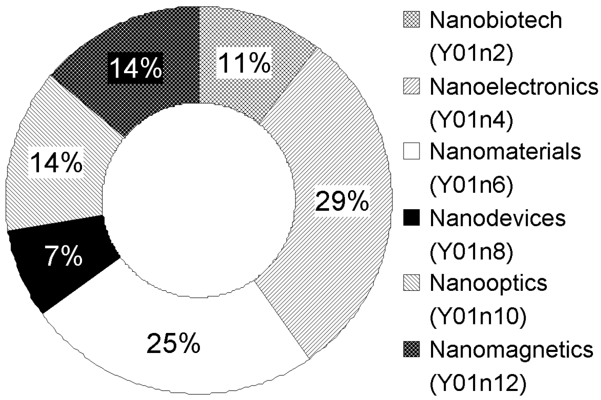

Figure 7. Nanotech patents worldwide according to EPO tag Y01N: distribution of tag classes Y01N2–Y01N12 in 2003.
Source: EPO (2006) and own calculations

Figure 7 shows that in 2003 the largest group of nanotechnology patents is related to nanoelectronics. Nanomaterials are on second place, followed with distance by nanomagnetics and nanooptics. Regarding the growth rates (not shown in the picture), huge differences occur between the fields. The overall growth rate of nanotechnology patents between 1995 and 2003 is at 14% annually with lower rates in the second period compared to the first period. Similar developments can be observed for nanoelectronics, nanomaterials, nanodevices and nanomagnetics, which had the highest growth rates in the 1990ies but lower ones (to even negative growth in case of nanodevices) between 1999 and 2003. On the other hand, nanobiotech and nanooptics had to undergo negative growth in the late 1990s, but increased to around 20% per year in the early 2000s. However, in absolute terms both are on a much lower level than nanoelectronics and nanomaterials. Therefore, this increase can not be seen as an early indication of the growing significance of nanobiotechnology for the market of nanotechnology products.

Regarding the countries of the applicants, the United States is the most active patenting application country in each subfield. But the countries on the following ranks change their position depending on the field. Germany, France and Canada rank higher for nanobiotechnology, the Netherlands and Sweden come up in nanoelectronics, while Belgium and Taiwan rank high in nanomaterials. Switzerland is, in particular, strong in nanodevices, and the UK in nanooptics. Observing two periods, the late 1990s and the early 2000s, some interesting shifts of centres of gravity can be observed. While the United States continued with a similar breakdown, Japan, Germany, France, South Korea and Canada moved towards nanomaterials. Germany, South Korea and in particular the Netherlands improved in nanoelectronics, while nanooptics gained weight in the United Kingdom, as did nanodevices in Canada and nanomagnetics in South Korea. Interestingly, the share of nanobiotechnology patents stagnated or decreased in each country analysed.

The scientific basis of nanotechnology: scientific publications and citations

Scientific publications are the most appropriate indicator for measuring scientific excellence by quantifying the output. However, the pure output number could be misleading; other indicators such as citations do reflect the quality of a scientific paper and its impact on the scientific community. Comparing the world regions, Figure 8 shows Europe in the lead in the number of scientific publications in nanotechnology.

In the 1990s, the European share still slightly increased, while the number of scientific publication originating from the USA and Canada decreased and especially 'other Asia', i.e. China, gained significance. Thus, it can be concluded that Europe has a large scientific basis in nanotechnology, comparable with its main competitors. 'Other Asia' is the most dynamic world region. A closer look at the different countries will shed some light at the origins of the nanoscientific publications (IGAMI 2006). Not surprisingly, the United States is most active with in total more than 18 000 nanoscientific publications from 1999 to 2004. Japan and China follow, but with a difference of 10 000 and more. The largest European countries Germany, UK, France and Italy are in position four to seven with publications between 7000 and 3000. South Korea, Canada, and Spain complete the top ten.

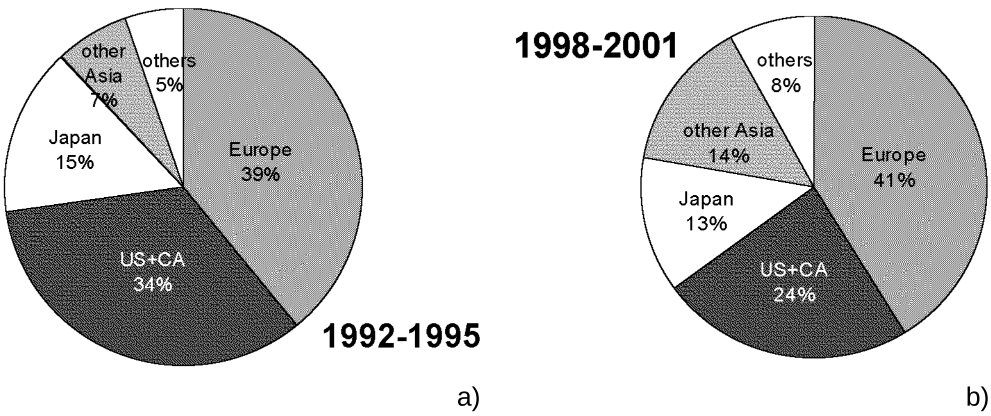

Figure 8. Scientific publications in nanotechnology in SCI database per world region, 1992–1995 and 1998–2001. "Europe" includes EU Member States and Associated Countries. Source: GLÄNZEL et al. (2003)

Not all scientific publications have the same quality and being active does not necessarily create an impact. A good indicator for the quality of a paper and thus its relevance and impact is the number of citations it receives. In the data, published by THOMSON ISI (2001), two small countries are in the lead: Switzerland and the Netherlands. The top three are completed by the United States. The other most active countries United Kingdom (represented here by England and Scotland), France, Japan and Germany are only in the midfield, behind Canada, Belgium, Ireland and Denmark. The three most dynamic countries Russia, China and South Korea complete the picture. The list of top cited countries in nanotechnology does also reflect a general phenomenon: If a country is English speaking or does not have a strong language in terms of numbers of persons speaking it, or it is multilingual, it has a far greater tendency for publications in 'world journals' in English language, which do have a higher impact than national language oriented journals with a smaller potential readership and thus a smaller impact.

The top cited journals for nanoscientific papers are the European *Nature* and the US *Science* (see THOMSON ISI, 2001). Both journals are multidisciplinary, which is very appropriate for nanoscientific publications. The vast majority of the nanoscientific high impact journals are in the fields of chemistry and physics, some are on materials research. Out of the top list, only 'Nanostructured Materials' is explicitly dedicated to nanoscience – with a relatively low impact rate and at the same time second highest number of nanoscientific articles.

These observations do support the interdisciplinary character of nanosciences: A nanoscientific article can be relevant for many disciplines and has thus the highest impact if the target community is broad – as it is the case for *Nature* and *Science* and the more general chemical and physical journals. Another, more general reason is that only high quality articles are accepted in these high level journals, which also leads to a larger number of cites. It can also be concluded that the nanoscientific performance of most of the European countries is ambiguous. European countries are either very active or with a high impact, while the United States, though very active, are also strong on the impact side.

Compared with the patent data, two most important conclusions can be drawn. First, neither for publications nor for patents, Europe is homogenous. There is no evidence for a *European paradox* but for a dispersed knowledge base and technological applications across Europe. Second, the United States is the benchmark when it comes to both scientific and technological excellence in nanotechnology. This conclusion is not new, but reinforced by evidence.

Conclusions

Empirical analyses of nanotechnology have to suffer from the limited access to reliable and comparable data and its complex nature. Official statistics do not identify nanotechnology at all, or link it to various different categories where it cannot be identified correctly, or the definition is at least questionable. Against this background, the initiative of the European Patent Office of identifying and labelling ('tagging') nanotechnology patents must be highly acknowledged. In other cases such as the market prospects and the company data, large scale surveys specifically dedicated to nanotechnology and have been carried out. These provide valuable information, but lack of comparability with data retrieved from other surveys. In this article, the weakness of the empirical base of economic and S&T data of nanotechnology has been taken into consideration by collecting data from different sources and pre-selecting them on the basis of reliability of the source, plausibility of the methodology and consistency with other data. It has been attempted to draw a most complete picture with the data available and to draw conclusions on their basis. It was not possible and not the intention of the author to generate data herself.

The empirical analysis of the economic development of nanotechnology obviously starts with the market prospects. Those prospects which referred to nanotechnology as a whole vary a lot and are shaped by the purpose for which they are intended. This is also due to the problem that real facts are not easy to measure and almost impossible to prospect. However, the data presented are sufficiently reliable because they are consistent and some anticipate the different paces in different nanotechnology fields and different important nanotech countries. Following this line, we can indeed expect a bright nanotechnology future. Because of its cross cutting character and its particular significance for the pharmaceutical and electronics industry, it has the potential easily to overtake the traditional biotechnology and even reach the level of the current situation with information and communication technologies.

These developments will have also a tremendous impact on the number of jobs in the manufacturing industries. Nanotech companies have been created in the past and much more are expected to emerge in the future. Unlike biotechnology, many of these companies will work in sectors where company size is less important for R&D, production or marketing. Once technologically successful, they will not necessarily be doomed to be acquired by a large company. This externalisation of high risk research, as observed as an R&D strategy in biotechnology for big pharmaceutical companies during the 1990s, will probably not occur to the same extent. Large and multinational companies are already committed to nanotechnology and spend a substantial amount of money for nanotech related research. In addition, risk capital for nanotech start up companies is available. Though not as optimistic as before the burst of the internet bubble, Venture Capitalists have discovered nanotechnology as the next big thing and follow with much attention and care the developments in the nanotech sector.

Regarding the financing of nanotech research, some differences between the world regions become obvious. In Europe, the private investors are lagging behind the public funding agencies. While the United States and Japan have a more balanced partition of private and public funding, the European nanotech research has to suffer from lower private funding sources. On the other hand and in order to put it positively, the public funding of nanotechnology in Europe is competitive on a world level and shows the early reaction of European research policy to the new opportunities opened by nanotechnology and the participation at the "nano-race". However, the lack of commitment of European private investors is not nano-specific – the same can be observed for the overall R&D expenditures as well and therefore has to be put down to other, more general reasons in the European industrial research system. The problem is well known and falls within the "Barcelona 3% – and 2/3 from industry – objectives" tackled on the European level (EUROPEAN COUNCIL, 2002).

The high level of public funding of nanotechnology research is very likely to have a positive impact on the S&T excellence of Europe. Knowledge and intellectual property are created in research projects which are to a great extent publicly funded. However, the successful technological implementation and the translation into commercially successful products depend also on the integration of industry in these projects, which is taking place but has to be improved. In this connection it can be considered as advantageous that Europe is focusing on civil applications of nanotechnology, other than e.g. the United States which spends a great share of its public funding of nanotechnology for military research. Another positive aspect of the substantial (civil) public funding in Europe is the societal dimension: Nanotechnology will have a positive impact on economic development – if it provides new solutions and does not create new problems. Only in this case will society in form of consumers, pressure groups and regulatory agencies accept and support nanotechnology products. The current discussions on the potential dangers of nanoparticles have to be addressed by contributing with research activities on the topic. Political action is also needed if risks turn out to be socially unacceptably high. The possibility to politically steer research, i.e. the definition of priority areas such as research on safety aspects of nanotechnology, on new environmental solutions, or on new medical devices, is one great advantage of publicly funded research. By influencing the direction of nanotechnology research, it can correspond to the societal expectations and consequently have a positive economic impact.

The political lessons learnt from the data are not new: Europe is doing well, but has to reduce a gap to the United States and Japan in many fields and for many indicators. In addition, Europe has to observe carefully the development in the emerging nanotech countries China, India and Russia. Much will depend on Europe's scientific and technological excellence in order to strengthen the nanotech knowledge base in research and industry and not to ignore the parallel need for well educated and world wide competitive nanotech workers and researchers.

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