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EVOLUTIONARY DYNAMICS AND SCIENTIFIC FLOWS OF NANOTECNOLOGY RESEARCH ACROSS GEO-ECONOMIC AREAS

Coccia Mario

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Evolutionary dynamics and scientific flows of nanotechnology research across geo-economic areas

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ABSTRACT: The purpose of this paper is to analyze, by concentration measures, metrics of dispersion and heterogeneity, the dynamics of the production of scientific output in nanosciences and nanotechnologies across worldwide economic players. The main result is that the concentration ratio of the production of nanotechnology research across different macro subject areas has been reducing over time and space, because knowledge dynamics of nanotechnology research has been spreading among new research fields and different industries. In addition, South Korea and China show higher performance than other countries in nanotechnology scientific products per million people. This scientific analysis is important in order to understand the current knowledge dynamics and technological trajectories in nanotechnology that may support future patterns of economic growth.

Keywords: Nanotechnology; Technological System; Technological Trajectories; Concentration; Changeability, Knowledge Dynamics

JEL Codes: L6; O3; Q57

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CONTENTS

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INTRODUCTION

Nanoscience and nanotechnology studies are flourishing in several countries and have begun to go beyond the bare entourage of research laboratories by a dynamic and continuous process of technology transfer towards key industries and sectors (*cf.* Bainbridge and Roco, 2006; Goddard III *et al*., 2007; Rickerby and Morrison, 2007; Robinson, 2009; Islam and Miyazaki, 2010). In fact, nanotechnological innovations have been fuelling current industrial dynamics in several niche industries such as microelectronics, microbiology, biochemistry, biotechnology, biomaterials, and so on. supporting competitiveness of firms by new products and processes for the well-being of modern societies (*see* Pilkington *et al*., 2009; Tegart, 2009; Glenn, 2006; van Merkerk and van Lente, 2005).

Nowadays nanotechnology is also creating new research centres, new communities of scholars, new journals, specific diploma and even PhD in nanotechnology. Hence, there is a vital interest to study the nanotechnology and the specificity of countries in nanoscience production and applications in order to explore the current knowledge dynamics of research trends that will drive future technological trajectories and patterns of economic growth (*cf.* Salerno *et al.,* 2008; de Miranda Santo *et al.*, 2006). In particular, as the field of nanotechnology experiences an exponential growth, many questions address not only *how* nanotechnology will develop across different research fields but also in *which* countries it is likely to develop.

The purpose of this paper is to analyze, by concentration measures, metrics of dispersion and heterogeneity, the production of nanotechnology researches across worldwide economic players to better understand possible trajectories of development in different scientific areas. As a matter of fact, the present research explores the knowledge dynamics of nanotechnology scientific production in different research domains, how different geo-economic regions (such as the North America and Europe) have been acting and reacting in nanotechnology researches, as well as the scientific collaboration of countries in nanotechnology research. As “nanotechnology is still in an early phase of development” (Renn and Roco, 2006, p. 153), this in-depth scientific analysis of research trends in nanotechnologies across leading worldwide players is an important topic to be developed in order to understand the current technological trajectories that may support future patterns of economic growth by countries.

This paper presents in section 2 a theoretical framework about nanotechnologies and nanosciences; section 3 describes the methodology of research, whereas section 4 analyzes the results and section 5 discusses lessons learned, linking the main results with the strategic needs of modern countries in highly competitive and turbulent markets.

1. NANOTECHNOLOGY: LITERATURE REVIEW AND SOME TERMINOLOGICAL ISSUES

Nanotechnology represents mostly an approach to science, technology and innovation rather than a specific research field by itself. “Nanoscience is the result of interdisciplinary cooperation between physics, chemistry, biotechnology, material sciences and engineering towards studying assemblies of atoms and molecules” (Renn and Roco, 2006, p. 154)[1]. Bozeman *et al.* (2007) quote the definition of nanotechnology given by National Nanotechnology Initiative’s (NNI):

[1] *Cf.* also Roco, 2007, pp. 3.1-3.26.

> ‘Nanotechnology is the understanding and control of matter at dimensions of roughly 1 to 100 nm, where unique phenomena enable novel applications. The diameter of DNA, our genetic material, is in the 2.5nm range, while red blood cells are approximately 2.5 m. Encompassing nanoscale science, engineering and technology, nano-technology involves imaging, measuring, modelling, and manipulating matter at this length scale. At the nanoscale, the physical, chemical, and biological properties of materials differ in fundamental and valuable ways from the properties of individual atoms and molecules or bulk matter. Nanotechnology R&D is directed toward understanding and creating improved materials, devices, and systems that exploit these new properties’ (pp. 807-808).

By one side the definition discriminates between science and technology, which is sometimes hard to tell. But on the other side, it describes precisely and briefly the fundamental characters of nanotechnology that acts in a well defined dimensional field in order to discover new behaviours and distinctive properties of materials when nanostructured. Shapira and Youtie (2008, p. 187) argue that: “Nanotechnology, which involves manipulating molecularsized materials to create new products and process with novel features because of nanoscale properties, is widely anticipated as one of the next drivers of technology- based business and economic growth around the world (President’s Council of Advisors on Science and Technology, 2005)”. These and other concepts show as, it is a difficult to provide a complete definition of nanotechnology because of conceptual and terminological issues. As a matter of fact, different scientific disciplines have in general a different approach towards nanotechnologies, as described by Balzani (2005). In Physics and Engineering the typical approach is the so-called *top-down*, where the matter is manipulated instrumentally – *e.g.* with the techniques of photolithography – in order to obtain the desired results: in this way the dimensional barrier of 100 nanometers has been a hard one to overcome. Whereas, in Chemistry, the approach is exactly reverse to previous one: a *bottom-up* approach where objects lying in the molecular dimensional domain – thus around and slightly below the nanometer – can be used as “bricks” to build nanostructured objects with bigger dimensions, such as the molecular computers with high scientific and technological content in the quest for an innovating application (Coccia *et al.,* 2010).

Therefore, as nanotechnologies have a “transversal” character, they find a vast application in several sectors and industries. The technological application of nanotechnologies has been first of all in niche industries, mostly knowledge-intensive and with high added-value products, such as the production of catalysts (*cf.* Zecchina *et al.,* 2007; Evangelisti *et al.,* 2007) or biomaterials produced for bone substitution inside the human body (*cf.* Bertinetti *et al.,* 2006; Celotti *et al.,* 2006). In these cases, the distance existing between basic research and technological innovation is almost not existing, or very narrow, and the high added-value of goods justifies the economic engagement of the scientific research. Other edge industries where the use of nanotechnologies is established are the biotechnologies and microelectronics. In these last cases the downscaling of circuitry – until the present limit of 45 nm (nanometers) – has mostly benefited of the extreme frontier of manipulation technologies in order to reach a higher miniaturization (Coccia *et al.,* 2010).

Economics of innovation argues that industrial dynamics is driven by various types of technical change, of different degrees in terms of socio-economic impact on geo-economic system, such as incremental innovations, radical innovations, new technological systems and technological revolutions (*cf.* Coccia, 2005). Freeman and Soete (1987, p. 56) defines new technological systems as: "innovations, which were technically and economically inter-related . . . . They include numerous radical and incremental innovations in both products and processes". Bozeman *et al.* (2007, p. 808) claim that: "Nanoscience and nanotechnology research … appear to have the potential to revolutionalize many sectors of industry, in particular by fostering the convergence between previously distinct technology-driven sectors". Nanotechnologies generates transversal technological innovations to possible industrial applications and are nowadays full inserted in the path of "creative destruction" of information and communication technologies (Bozeman *et al.*, 2007). Shapira and Youtie (2008, p. 187) state that: "Current research suggests that nanotechnology may be deployed as a general-purpose technology that is broadly applicable across the economy with pervasive effects". In fact, the convergence of nanotechnology, biotechnology and information technology (Bainbridge and Roco, 2006) generate clusters of radical innovations that improve the economic behaviour and "competitive advantage" (Porter, 1990) of countries in several markets. In addition, Nordmann (2004) proposes a European approach for Converging technologies, namely the Converging Technologies for the European Knowledge Society (CTEKS) within its report: this novel and specific character of converging technologies opens up a wide space for technological development. Hence, nanotechnology, considering these arguments, can be considered a new "technological system" having the potential to change many scientific and technological fields, generate new products and processes, as well as redefine existing industries and create new ones. In other words, competitiveness and economic growth of modern economies are also driven by nanotechnologies which may support, converging with other technologies, the next Kondratieff wave (Coccia, 2010, 2010a).

Renn and Roco (2006, p. 154) argue:

> As with other new technology, nanotechnology evokes enthusiasm and high expectations: for new progress in science and technology, new productive applications and economic potential on one hand; and for concerns about risks and unforeseen side effects on the other.

Renn and Roco (2006) also claim the general risks associated with nanotechnology applications, showing that the nanotechnology innovation proceeds ahead of the policy and regulatory contexts: "Governance gap is . . . especially significant for the several 'active' nanoscale structures and nanosystems that . . . have the potential to affect not only the human health and the environment but also aspects of social lifestyle, human identity and cultural values" (p. 153, original emphasis). Robinson (2009) describes the notion of "*Responsible Research and Innovation* of nanotechnology as an opportunity to develop support tools for exploring potential co-evolutions of nanotechnology and governance arrangements" (p. 1222, original emphasis).

Guan and Ma (2007, p. 881, original emphasis) argue that: "In comparison to other fields of science and technology, there is no readily available subject category or classification system for nanoscience and nanotechnology. Furthermore, no agreements have been made on the definition of the nano-community". Therefore, as there are terminological and main normative issues about these new technologies, we consider a broad-based definition of nanotechnology to analyse its knowledge dynamics. This approach is comprehensive and reliable on a large scale because of interdisciplinary effects of nanotechnology research (*cf.* Leydesdorff, 2008). In order to study the dynamics of this main research field, "Bibliometric quantification is an effective way to show the emergence and development of a new technology . . . . Over the past few years, several attempts have been made to study nanoscience and nanotechnology in a bibliometric manner (Guan and Ma, 2007, p. 881; *cf.* Leydesdorff, 2008; Porter *et al.*, 2008). Salerno *et al.* (2008), analyzing future developments in nanotechnology, argue that: "Bibliometric analysis of publications … can help have a synthetic picture of the best players at a worldwide level, their lines of inquiries and their relationships, that is, they could help to cope with the extremely fragmented knowledge, actors and applications involved in the evolution of the field" (p. 1220). In fact, scientometric indicators are effective tools to analyze the research fields in nanotechnology (cf. Braun *et al.*, 1997) and Kostoff *et al.* (2007) discuss several global nanotechnology metrics. Leydesdorff and Rafols (2009), showing a global map of science, present some positive and negative sides of scientometric analyses. The literature is vast and not fully cited here, but a good list of references is found in Kostoff *et al.* (2007a), Shapira and Youtie (2008).

Hence, as the field of nanotechnology has been experiencing rapid growth, many modern questions are focused on *how* nanotechnology will develop across research domains and *where* (countries) it is likely to develop. This research, in order to probe the knowledge dynamics of the production of nanotechnology and to explore emerging scientific domains, applies concentration measures, metrics of dispersion and heterogeneity that are described in the next section.

2. SOURCES AND STRATEGY OF ANALYSIS

This paper uses Scopus as database. Scopus is a widely accepted database covering most of the important influential journals in natural and social sciences (Scopus, 2011)[2]. Scopus exploits a system of classification of titles under categories: "four broad subject clusters (Life Sciences, Physical Sciences, Health Sciences and Social Sciences & Humanities) which are further divided into 27 major subject areas and 300 minor subject areas. Titles may belong to more than one subject area"[3]. Subject areas can be a proxy about the main content of research outputs.

Data mining from Scopus (2011) on nanotechnology topics is based on:

- the following main search string that considers the intersection of the term nano in the abstract of papers and some keywords: Nanostructured materials OR Nanotechnology OR Nanostructures[4]. This methodological analysis, strictly speaking, considers research outputs that have mainly the content focused on nanotechnology topics.
- research string focuses on publications per country, therefore scientific products retrieved are counted only one time, avoiding problems of multiple versions of the same article.
- Main documents retrieved are: Articles, Conference Papers, Reviews, Letters, Editorials, Short Surveys,

[2] http://info.scopus.com/about/ (accessed 11January 2011);
http://info.scopus.com/why-scopus/academia/(accessed January 18th, 2011).

[3] http://info.scopus.com/scopus-in-detail/content-coverage-guide/journalclassification/ (accessed January 18th, 2011).

[4] Guan and Ma (2007, p. 881, original emphasis) claim that: "The only way to approach 'nanoscience and nanotechnology' in a bibliometric respect appears to be through keywords".

Conference Reviews, Notes and Books.

- Scientific outputs carried out by Academic laboratories, Government founded labs and Company labs operating in the vast research field of basic research on nanotechnology as well as on its industrial applications. Research institutions are universities, but there are a lot of government founded labs (e.g. California Institute of Technology-USA, Istituto Nazionale per la Fisica della Materia-Italy, Max Planck Institute for Metals Research and for Polymer Research-Germany, etc.) as well as company labs (for instance: Alps Electric Co. Ltd., Asahi Grass Co. Ltd., Canon, Hoya Corporation, ITES Co. Ltd., JEOL Ltd., NANOMIZER Inc., NEC Corporation, Nikon Corporation, Nisshin Steel Co Ltd, Zyvex Corporation, IBM Almaden Research Center, Hewlett Packard Laboratories, Alcatel-Lucent, 3M, ELETTRA Sincrotrone Trieste S. C. p. A, and so on).
- Time Horizon from 1996 to 2008 in order to analyze the research trends. Within the range 1996-2008 there is the opportunity to retrieve all information analyzed, whereas this is not possible for year before 1996 (when Scopus starts gathering full data).
- Key geo-economic areas are: USA and Canada, South Korea, Japan, China and Europe[5]. These geo-economic and geo-politic areas are the main worldwide players in the production of nanotechnology and nanoscience researches.
- Content-related analysis of nanotechnology researches is based on subject areas provided by Scopus.

The quantitative data retrieved from Scopus provide main information about several characteristics of the scientific production on nanotechnologies. In particular, the research explores the diffusion over time of papers in nanotechnology finding a match for subject areas of journals that represent strong indicators for tackling the emergence of new scientific fields and applications in nanotechnology. In particular, the *affiliations* of papers (*i.e.* main research institutions and/or labs where the research is carried out by scholars) and the *subject areas*[6] of nanoscience and nanotechnology researches published on leading scientific journals are considered. The sample of this research is based on 149,324 scientific products (*e.g.* papers, proceedings, etc.) on nanotechnology researches with their affiliations retrieved per country and year. The sample includes about 96% of main research centres operating in nanotechnologies. As papers concerning the nanotechnology researches are published on journals that are classified per 28 subject areas[6], the 149,324 scientific products have almost 400,000 occurrences of subject areas. In general, the number of the occurrences of subject areas by journals is greater than the total number of scientific products (*i.e.* papers)[7]. In particular, subject areas represent a good proxy of main *content* of papers, since it is impossible to in-depth analyze 149,324 abstracts and texts of all

[5] In "Europe" the selected countries are: Albania, Austria, Belarus, Belgium, Bosnia, Bulgaria, Croatia, Czech Republic, Estonia, Finland, France, Germany, Greece, Holland, Hungary, Ireland, Italy, Latvia, Lithuania, Macedonia, Moldova, The Netherlands, Norway, Poland, Portugal, Romania, Russia, Serbia, Slovakia, Slovenia, Spain, Sweden, Switzerland, Ukraine, and United Kingdom.

[6] Scopus classifies journals in major subject areas, such as one of which is "Energy". Journals can be allocated to multiple subject areas as appropriate to their scope. I use all subject areas containing papers on nanotechnology studies.

[7] For instance a paper about the nanotechnology published on the journal *Scientometrics*, is one paper with 3 subject areas, since *Scientometrics* is classified with three subject areas (computer science applications, social sciences and library and information sciences).

scientific output retrieved. In order words, empiricist-positivist approach of this research is integrated by an interpretivist one that considers the occurrences of articles in nanotechnology researches per subject areas alike a view to investigate *how much* attention some research fields have received in the scientific literature. This approach is important to better explore knowledge dynamics of nanotechnology by possible trajectories of development in different scientific areas.

The vast sample of papers (outputs) classified by Scopus in main subject areas has been aggregated in five "Macro Subject Areas": Material Science, Chemistry and Medicine, Physics and Earth Sciences, Engineering; all marginal areas of nanotechnology researches (less than 5% of the sample) have been included under the category "Others" (*i.e.:* Information and Mathematics Sciences, Social and Economic Sciences, Energy, Environmental Science). This paper considers the occurrences of papers in nanotechnology per macro subject areas at country level in order to apply the methodological techniques described later. Table 1A in Appendix shows the number of papers per subject areas and Macro Subject Areas, as well as the content of each Macro Subject Area. This aggregation is comprehensive on large scale, and it shows the temporal and spatial patterns of nanotechnology research trends across countries, reducing distortions in terms of attribution of papers to each subject category. In fact, the analysis per keywords has not been considered, first of all because of the high number of generic keywords like "Synthesis", "Chemistry", "Priority journal", "Crystallization", "Methodology" etc. In addition, the categorization of research domains in "nanomaterials", "nanoelectronics", etc. is not reliable because there are inner overlaps, making such analysis less meaningful: in fact, nanomaterials are heavily applied in nanoelectronics; therefore, this categorization is not fruitful for investigating the real nanotechnology research trends and could bring to ambiguous and misleading results. *Vice versa*, the aggregate sets applied in this research (*i.e.* macro subject areas) provide more accurate, consistent and robust results about the temporal and spatial research trends across countries. The information analysis of the sample is carried out by concentration measures, metrics of dispersion and heterogeneity, in order to explore and compare research trends in nanotechnology researches across countries.

Economic literature shows the interesting research by Shapira and Youtie (2008, pp.191 ff.) that measure regional economic concentration using the Herfindahl index, whereas Guan and Ma (2007, p. 885) apply the Theil's entropy index to investigate the citation inequality.

Following indices have general applications in statistics, providing main information on key aspects of statistical distributions and are apt measures for probing the data.

- *Concentration at country level over time*. R Gini's ratio of concentration measures the degree of concentration of nanotechnology research per country over time if:

  x_{ji} = total number of occurrences of nanotechnology research publications of the *j-th* country in a macro subject area *i-th*;

  A_i = cumulative values of x_{ji};

  p_i is i/N (N is total number of macro subject areas), while q_i is A_i / A_N.

$$R_{j\ t} = Ratio\ \ of\ \ concentration = \frac{\sum_{i=1}^{N-1}(p_i - q_i)}{\sum_{i=1}^{N-1} p_i} \qquad [1]$$

$$j = country\ (e.g. USA);\ t = time (e.g. 2000)$$

$$per\ all\ macro\ subject\ areas\ i \in [Basic\ and\ Earth, Chemistry\ and\ Medicine, Engineering, Material\ Sciences]$$

Gini's ratio of concentration R is calculated per country for t= *1996, …, 2008.* It ranges between 0, when there is no concentration (perfect equality), and 1 when there is total concentration (perfect inequality).

The robustness of this analysis is supported by:

- *Changeability or heterogeneity indices* (absolute and relative) *at country level over time per all macro subject area i* ∈[Basic and Earth, Chemistry and Medicine, Engineering, Material Sciences]

Index absolute of changeability or heterogeneity (Gini) per country j for t= 1996, …, 2008 is:

$$E_{j\ t} = 1 - \sum_{i=1}^{s} y_i^2 \qquad [2]$$

where $y_i = \frac{n_i}{N}$ (n_i are the total number of occurrences of nanotechnology research publications in a macro subject area *i-th* of the *j-th* country, in the year t; N= is the total value). At country level this index is calculated for all nanotechnology research publications across different macro subject areas.

Index of Entropy is:

$$H_{j\ t} = -\sum_{i=1}^{s} y_i log y_i \qquad [3]$$

$$MaxE = \frac{s-1}{s}; \qquad MaxH = log\ s$$

Relative indices are:

$E / Max\ E$ and $H / Max\ H$

Remark: Lower values of these indices indicate high concentration, higher E and H indicate proportional distribution (low concentration);

- *Inequality index across different research domains.* It compares two distributions of research fields, in order to see the mutual dynamics over time; this index is given by:

$$M_{|x1-x2|} = \frac{\sum_{1=1}^{N}|x_{1i} - x_{2i}|}{N}\ ;$$

computed on each couple of values within two distributions X_1 and X_2 (*e.g.* papers in different research domains: Material *vs.* Chemical sciences). If the values of these distributions are ranked from min to max values $x_{(i)}$, the index of dissimilarity is:

$$D_{|x1-x2|} = \frac{\sum_{1=1}^{N}|x_{1(i)} - x_{2(i)}|}{N};$$

$$MaxD = \mu_1 + \mu_2 - \frac{2 min(\mu_1, \mu_2)}{N};$$

where μ is the arithmetic mean of the distribution.

The relative index of dissimilarity is:

$$D_r = \frac{D}{MaxD} \in [0,1] \qquad [4]$$

- *Indices of connectedness* to analyze the spatial collaboration links, over time, among pairs of geo-economic areas producing nanotechnology research (*i.e.* Countries and collaborators). The statistician Gini suggests of measuring the connectedness by the following indices η and η_1 :

$$\eta = \frac{\sum_{i=1}^{s}\sum_{h=1}^{t}\left|Nn_{ih} - n_{i0}n_{0h}\right|}{2\left(N^2 - \sum_{h=1}^{t} n_{0h}^2\right)} \qquad [5]$$

η is the connectedness index of the consequent statistical character *y* (papers of collaborator countries carry out with institutions/researchers of country A) from precedent character *x* (country A); this index has a range from 0 if the statistical characters are independent, whereas 1 if there is a max connexion of *y* from *x*.

$$\eta_1 = \frac{\sum_{i=1}^{s}\sum_{h=1}^{t}\left|Nn_{ih} - n_{i0}n_{0h}\right|}{2\left(N^2 - \sum_{i=1}^{s} n_{i0}^2\right)} \qquad [6]$$

η_1 is the connectedness index of the consequent statistical character *x* from precedent character *y*. *Mutatis mutandis*, the range of this index $\eta_1 \in [0,\ 1]$.

If it is not possible to detect a precedent statistical character, the index of connexion A (that measures the interdependence) is given by geometric mean of the above indices of connectedness η *and* η_1 :

$$A = \sqrt{\eta \cdot \eta_1} \qquad [7]$$

Index A is an appropriate measure of the association of variables; it ranges from 1 (max *bijective* connection between statistical characters) to 0 that indicates statistical independence. These indices have been applied to analyze the connectedness and connexion between geo-economic regions "A" of the origin of nanotechnology study (*e.g.* East geo-economic areas) and geo-economic regions of foreign scholars and institutions collaborating in this nanotechnology study (*e.g.* West geo-economic areas) with "A". Guan and Ma (2007, pp.882-883) show a similar analysis of collaboration profile of countries applying a different approach.

3. EPISTEMOLOGICAL POSITION AND EMPIRICIST-POSITIVIST ANALYSIS

This paper analyzes the production of nanotechnology researches in five main geo-economic areas, based on data of research labs and their scientific outputs collected by Scopus (2011). As far as the structure of domestic research labs producing nanotechnologies (Academic laboratories, Government founded labs and Company labs), the highest number is in Europe and North America (*i.e.* USA and Canada). In fact, Europe and North America have in 2008 about 150 research labs operating in nanotechnology fields. Japan has an average number of research labs lower than previously leading geo-economic areas, with roughly 100 units. China and South Korea are two geo-economic areas where the number of nanotechnology research labs has been increasing over time, reducing in 2008 the high gap presents in 1996 in comparison with Europe and North America[8]: in particular, China has more than 130 nanotechnology research labs operating in 2008 (Table 2A in Appendix shows the cumulative number of these research labs over time and across geo-economic areas, and their scientific outputs).

[8] Cf. also de Miranda Santo *et al.* (2006, pp. 1022ff), Guan and Ma (2007).

Table 1: *Percentage of nanotechnology research per type of research labs and geo-economic areas*

	(%)				
year 2008	University	Public labs	Company labs	Unknown	Total
China	85.73	14.27	0.00	0.00	100
Europe	80.34	18.73	0.93	0.00	100
Japan	67.61	25.70	6.44	0.25	100
South Korea	76.54	19.36	3.80	0.30	100
USA & Canada	84.91	10.80	3.57	0.72	100

Table 1 shows the scientific production per type of research labs: Nanotechnology researches have been carried out mainly universities across all geo-economic players, but public labs have a higher percentage of production in Japan 25.70%) and South Korea (about 20%), whereas USA &Canada have a mere 10.8%. Japan has also the higher percentage of company labs operating in nanotechnology (roughly 6.5%), Europe the lowest (0.93%).

Instead, Tables 3A-5A in Appendix show as in 2008, the most prolific institutions in nanotechnology research are 35% in China and 30% in Japan, whereas in 2002 and 1996, 35% of research institutions were in Japan and 25% in USA[9].

As nanotechnology researches are growing over time, this paper assumes the following epistemological position:

> nanotechnology researches has been having a widely diffusion of the research production among different research domains and new technological trajectories.

Figure 2, based on index [1], shows a moderate concentration ratio of nanotechnology researches across geo-economic areas (in general the concentration ratio R on *y*-axis is less than 0.5): in China and South Korea, R is higher than Europe and North America. In particular, figure 1 shows a declining trend of concentration ratio across geo-economic regions as function of time: this means a diversification of nanotechnology research among different macro subject areas by a widely develop in new scientific fields. The underlying causes of this declining concentration ratio over time can be due to: China in 1996 had a high concentration of the production of nanotechnology researches in material science (52.41% of total), as well as a similar behaviour there was in South Korea (50.79% of total), USA and Canada (45.23%), Europe 41.54% and Japan 38.93% (cf. Table 6A in Appendix). In 2008, the production of nanotechnology researches in material science across countries is considerably decreased and the current distribution of nanotechnology researches has more uniformity among different macro subject areas, generating lower concentration ratios (see tab. 6A in Appendix-year 2008). These patterns across countries confirm the development of nanotechnology research in different scientific fields that represent possible future technological trajectories in the techno-economic paradigm of the "converging technology".

9 Guan and Ma (2007, p. 884) show a similar table based on a different period of time.

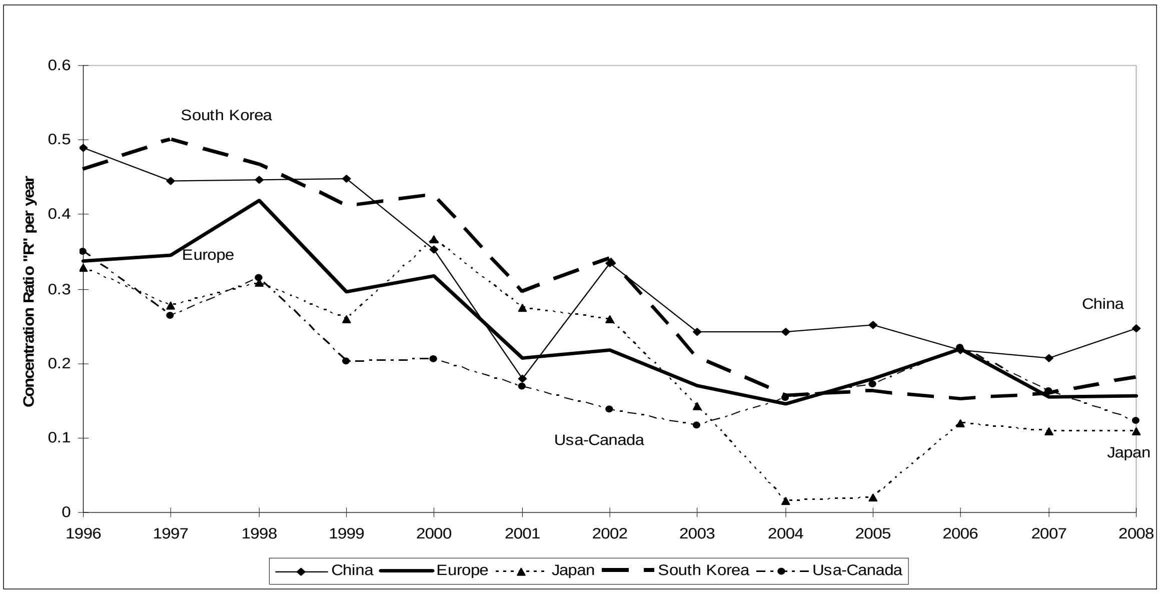

Figure 1:*Concentration ratio "R" based on production of nanotechnology researches across geo-economic areas as function of time*

Figure 2 presents the changeability measured by relative index of Gini (E*), index [2] in the methodology, that has a dynamics similar to Entropy index (H* index [3])

These indices show the growing trends across geo-economic areas as functions of time and confirm the concentration ratio results: *i.e.* the productions of nanotechnology researches in the past (1996-1998) were more concentrated on specific research fields (*e.g.* material, physics and earth sciences), generating lower E index; this concentration has been reducing over time and space, increasing the heterogeneity (high heterogeneity= high index E* and H*, in our case E* $\in$[0.76; 0.80] over 2006-2008 period) by a rather widely production of nanotechnology researches across different macro subject areas that confirm the spreading of radical and incremental innovations of this "technological system" among new research fields.

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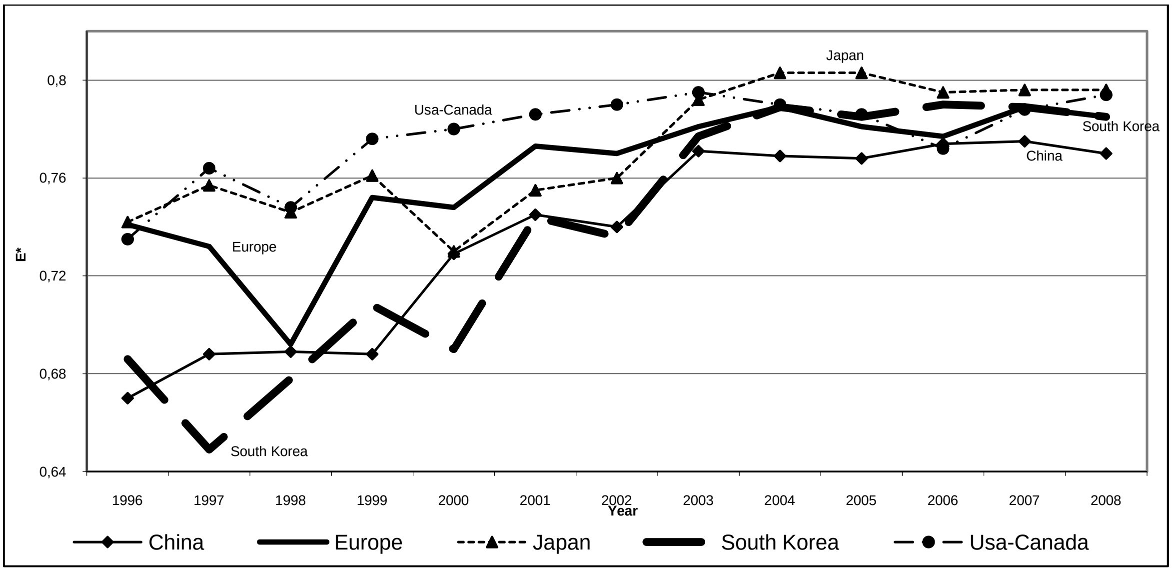
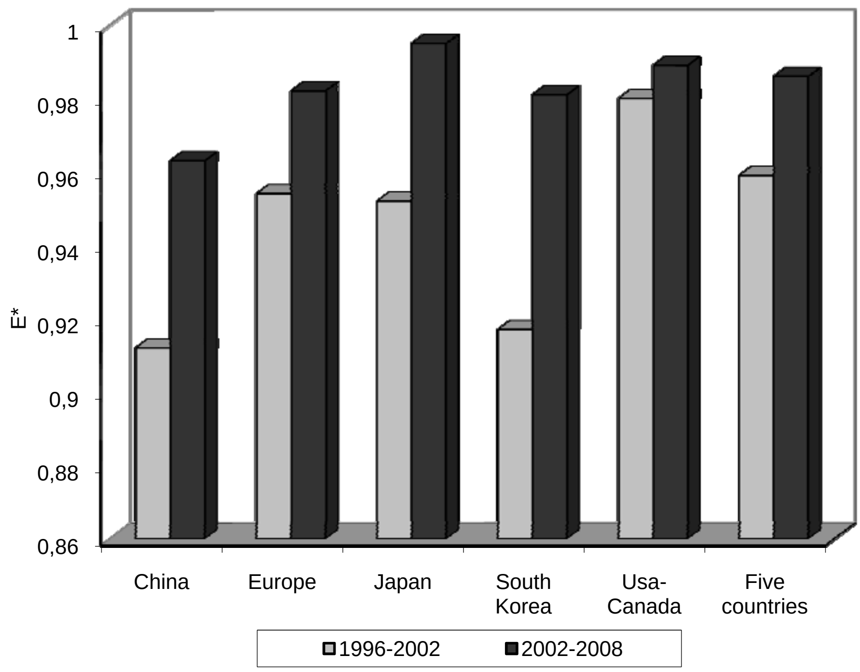


Figure 2: *Index of changeability E* based on production of nanotechnology researches as function of time*

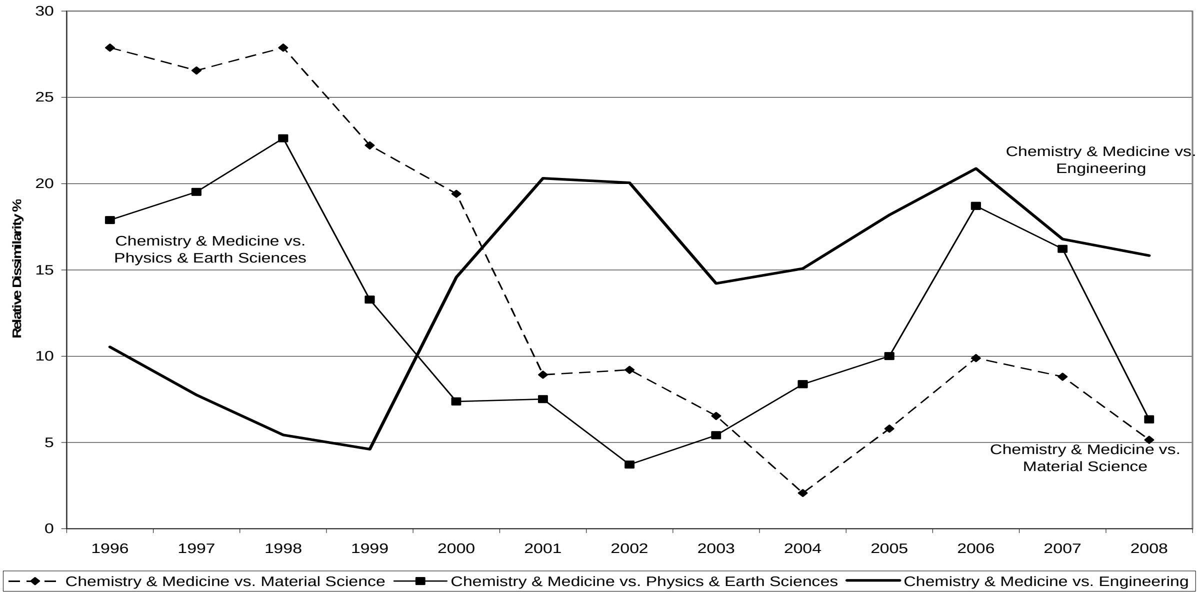
These changeability indices, over 1996-2001, are lower in China and South Korea, where there was a higher concentration of nanotechnology researches in chemistry and medicine, and material science, whereas over 2001-2008, E and H indices in Japan are higher than other geo-economic areas because of a rather uniform distribution of the scientific production in nanotechnologies across different macro subject areas. (*cf.* fig. 3)

Main results about the divergence between two statistical variables, over time are provided by index of inequality, inequality across arithmetic mean, index of dissimilarity (ranking values) and relative dissimilarity % (index [4] in the methodology).The divergence of the production of nanotechnology among key macro subject areas has been reducing over time (see fig. 4, 1996 *vs.* 2008 year), *e.g.: a*) relative dissimilarity (%) between physics-earth science *(and)* chemistry and medicine, *b*) between material sciences *(and)* chemistry and medicine; whereas it has been increasing between engineering *(and)* chemistry and medicine (*c*). The reduction of divergence confirms that the scientific production of nanotechnology researches among macro subject areas has similar patterns of development in different areas, *vice versa* in case of increase.



Note: E = Index of changeability (Gini) behaviour is similar to H = Entropy

Figure 3: *Index of changeability E* based on production of nanotechnology researches across geo-economic areas*



Note: values of China, Europe, Japan, South Korea, USA-Canada

Figure 4: *Relative dissimilarity % comparing macro subject areas as functions of time*

Figure 5 displays the highest relative increase % of the production of nanotechnology researches over 1996-2008 in the chemistry and medicine research field (the lowest is material science), however if this analysis is restricted to 2002-2008 period, fig. 6 shows a high percentage of nanotechnology research is Engineering.

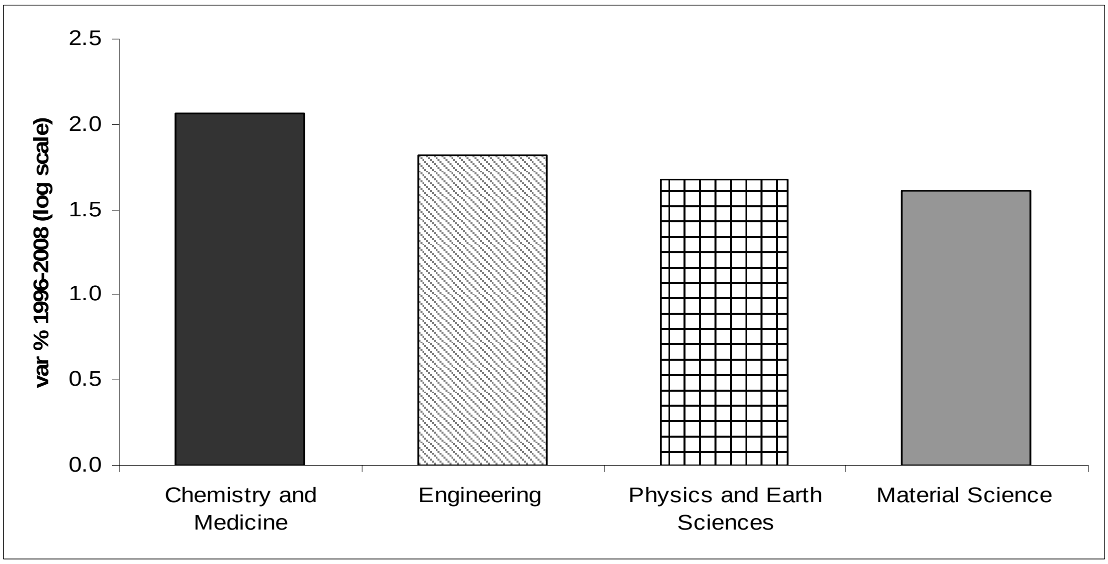


Figure 5: *Increase (%) of nanotechnology research per macro subject areas over 1996-2008*

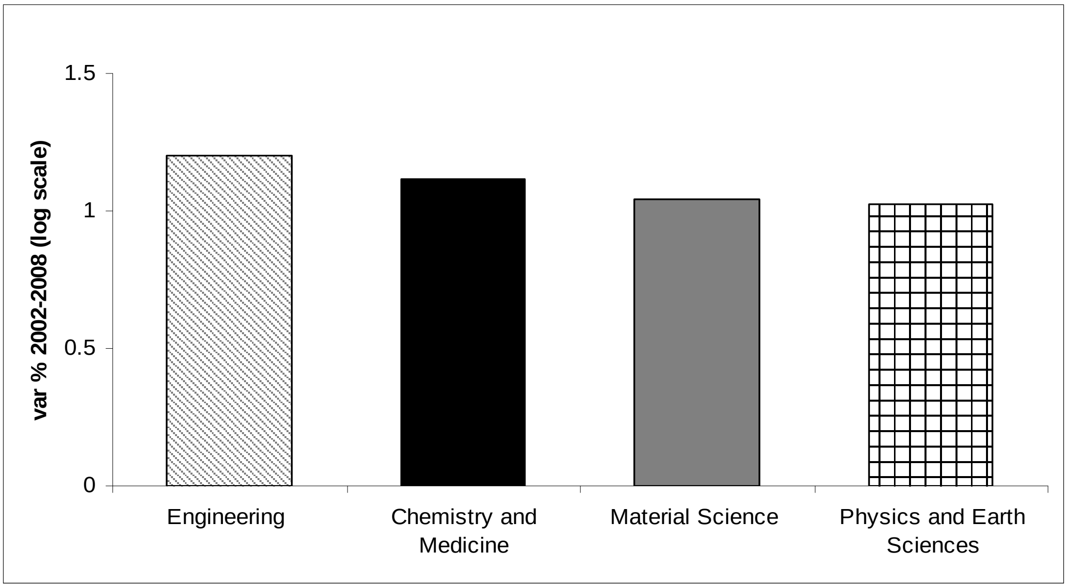


Figure 6*: Increase (%) of nanotechnology research per macro subject areas over 2002-2008*

In addition, data show that the country high performer in almost all macro subject areas is South Korea , whereas China has the leadership of relative increase % of the production of nanotechnology researches in material sciences; low performers change according to research fields of nanotechnology researches, *e.g.* Europe in chemistry and medicine, Japan in engineering, physical and earth sciences, USA and Canada is in material sciences.

As far as the scientific collaboration in nanotechnology researches across geo-economic areas, indices (η, η_1, A, see Equations [5], [6] and [7]) show good connexion of the production of nanotechnology researches between region α of the origin of nanotechnology research *and* other regions of foreign scholars and institutions collaborating in the nanotechnology research with the region α. Although each geo-economic area has a vast production of scientific outputs within domestic nanotechnology research labs (about 90%), the residual is carried and research labs. This connexion has been increasing over time (period 1996-2002 *vs.* 2002-2008, see tab. 1): this indicates an increasing temporal intensity of scientific collaborations in nanotechnologies across main geo-economic players.

Table 1: *Indices of connectedness η and connexion A*

	Indices	1996-2002	2002-2008
Regions of origin of nanotechnology research (and) Regions of foreign scholars and institutions collaborating in the nanotechnology research	η =	0.3527	0.4117
	$\eta 1$ =	0.3155	0.3736
	A =	0.3336	0.3922

Table 2: *Indices of connectedness η and connexion A between East and West geo-economic regions*

	Indices [1)]	1996-2002	2002-2008
East Regions of origin of nanotechnology research (and) West Regions of foreign scholars and institutions collaborating in the nanotechnology research	η^* =	0.0783	0.2281
	$\eta1^*$ =	0.0610	0.1330
	A^* =	0.0691	0.1742

Note: indices of connectedness (η*, η1*) of *East* regions (e.g. China, South Korea, etc.) of origin of nanotechnology researches from *West* regions (e.g. European countries, North American countries, etc.) of foreign scholars and institutions collaborating in the nanotechnology research with the East regions.

In particular, the indices of connectedness (η*,η1* and connexion A) of *East* regions of the origin of nanotechnology research (i.e. China and South Korea) from *West* regions of foreign scholars and institutions collaborating in the nanotechnology research with East regions (i.e. Europe and North America), have been increasing over time (see tab. 2).

4. MAIN FINDINGS AND CONCLUDING REMARKS

The aim of this paper is to explore the knowledge dynamics of the production of nanotechnology research in order to better understand current trajectories of development of nanotechnologies in different scientific fields.
Main results are:

- Europe and USA-Canada have the highest number of nanotechnology research labs, although the key role of China has been increasing over time[10]: in 2008 the most prolific institutions in nanotechnology are 35% in China and 30% in Japan.
- Concentration ratio of nanotechnology researches across research fields has been reducing over time, confirming the widely spread of nanotechnology research across different research areas by the emerging of new trajectories of development of nanotechnologies in new scientific domains (epistemological position);
- The highest relative increase % of nanotechnology research over 1996-2008 has been in the chemistry and medicine research field, however if this analysis is restricted to 2002-2008 period, the research field with high percentage of nanotechnology research is Engineering science.
- The percentage increases of nanotechnology researches show that almost in all macro subject areas the country high performer is South Korea, whereas China has the leadership of nanotechnology researches in material sciences.
- The patterns of scientific collaborations between geo-economic areas in nanotechnology researches have been increasing over time and show the high connectedness of East regions from West regions collaborating in the nanotechnology research.

This framework and results are important to ask some vital questions:
Why concentration ratio of the production of nanotechnology researches among scientific fields has been reducing?

[10] *Cf.* Shapira P., Wang J. (2009) for strategies and issues in the commercialization of nanotechnology in China.

This concentration has been reducing over time and space because of a rather widely development of the production of nanotechnology researches across different macro subject areas (high heterogeneity): this confirms the spreading of radical and incremental innovations of this "system of nanotechnology" among new research domains and different industries.
Why relative production of nanotechnologies in "Chemistry and Medicine" and "Engineering" has been increasing, whereas in "Material Sciences" has been decreasing?
Relative decrease over time of the production of Nanotechnology researches in "Material science" and increase in "Chemistry and Medicine" and "Engineering" can be due to the current technological trajectories of development of nanotechnology that have been passing from the *invention phase* of new nanomaterials to the *innovation phase* focused on innovative applications in biochemistry, biomaterials, genetics, microbiology, etc.: in other words, nanotechnologies is a dynamic and active "new technological system" (Freeman and Soete, 1987, p. 56) with a current technological change. Islam and Miyazaki (2010) argue that: "US has gained much strength in bionanotechnology research relative to other domains, and the other regions (e.g. the EU, Japan, China, South Korea and India) have gained their research strength in nanomaterials, nanoelectronics and nanomanufacturing and tools" (p. 229). In addition, this current "technological system" has different inner trajectories that, by a cross-fertilization with other scientific and technological domains, have been generating "converging technologies" (Bainbridge and Roco, 2006)[11] that have been creating new products and processes that will generate new radical and incremental innovations in not-too-distant future, as well as emerging industries within the new techno-economic paradigm of information and communication technologies (cf. Coccia at al., 2010).
Although the study can have distortions, the aggregation category per macro subject areas should limit some problems, providing comprehensive and reliable results on a large scale. The main limit imposed by Scopus search engine is the maximum of 160 items (the most representative ones) for each data mining. Moreover, although the critical findings of this research on the current dynamics and worldwide patterns of nanotechnology researches, the results could be improved because the dataset Scopus is a relatively new instrument for scientific literature classification and not all nanotechnology researches might be included (this limit is common with other web-based datasets). In the future these important datasets could have a broad covering of scientific products and refined search options. In addition, content analysis is based on subject areas provided by Scopus, which provide reliable results on large scale, though can have some limits due to overlap issues of scientific outputs across different subject areas assigned by Scopus per each journal.
This paper, in particular, has showed the occurrences of articles per subject areas that indicate *how much* attention some research fields have received in the scientific literature by studies in nanotechnology research carried out by scholars within institutions. This could be a proxy of future technological trajectories as well as of emerging research domains in nanotechnology.
To sum up, the main results of this paper shows a broad diffusion of nanotechnology researches among different research domains and the current new growing applications of nanotechnology in some key scientific fields of the Chemistry,

[11] It is important to note that Roco and Bainbridge by National Science Foundation coined the term of converging technologies in NBIC Report in June 2002.

Medicine and Engineering[12]. As far, linear research trends, they show potential trajectories of development of nanotechnology that should be further explored to provide more accurate results for forecasting purposes.

No doubt that information analysis and foresight researches for research trends of nanotechnologies are a hard work since this technological system is characterized by current "interdisciplinarity" and "pervasiveness" of researches (Salerno *et al.*, 2008, p. 1206, 1208, and 1220, *passim*). In presence of these scientific and analytical issues, further investigations with different techniques and datasets about possible research trends of development of nanotechnology are needed to design provident innovation policy and governance practices aimed at fostering the scientific research within this driving technological system in order to support modern competitiveness of firms and emerging industries for future economic growth of countries in fast-changing markets.

[12] According to de Miranda Santo et al. (2006): "many areas will suffer impacts caused by Nanoscience and Nanotechnology … as health, chemistry and petrochemicals, computing, energy, agribusiness, metallurgy, textiles, environmental protection, among other" (p. 1020).

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Appendix A

Table 1A: *Scientific output in nanotechnology studies over 1996-2008 per subject areas and macro subject areas*

	Macro Subject Area	*Subjects Area (S.A.) of Scopus per Journals**	*Total papers in S.A.*	*Total papers in Macro S.A.*	*%*
	Material Science	Materials Science	117,808		29.46
				117,808	
	Chemistry and Medicine	Biochemistry, Genetics and Molecular Biology	14,471		3.62
		Chemical Engineering	24,617		6.16
		Chemistry	56,329		14.09
		Dentistry	212		0.05
		Health Professions	376		0.09
		Immunology and Microbiology	889		0.22
		Medicine	5,677		1.42
		Veterinary	42		0.01
		Neuroscience	336		0.08
		Nursing	30		0.01
		Pharmacology, Toxicology and Pharmaceutics	3,855		0.96
				106,834	
	Physics and Earth Sciences	Earth and Planetary Sciences	1,555		0.39
		Physics and Astronomy	88,418		22.11
				89,973	
	Engineering	Engineering	65,421		16.36
				65,421	
Others	**Information and Mathematics Sciences**	Mathematics	2,061		0.52
		Computer Science	5,794		1.45
		Decision Sciences	86		0.02
				7,941	
	Social and Economic Sciences	Arts and Humanities	266		0.07
		Business, Management and Accounting	562		0.14
		Economics, Econometrics and Finance	82		0.02
		Multidisciplinary	2,412		0.60
		Psychology	75		0.02
		Social Sciences	680		0.17
				4,077	
	Energy	Energy	3,921		0.98
				3,921	
		Agricultural and Biological Sciences	770		0.19
	Environmental Science	Environmental Science	3,086		0.77
				3,856	
TOTAL			**399,831**	**399,831**	**100.0**

**Note:* Scopus classifies journals in major subject areas, *e.g.* "Energy". Journals can be allocated to multiple subject areas as appropriate to their scope. The subject areas contain scientific products concerning nanotechnology studies.

Table 2A: *Cumulative research labs in nanotechnology and their scientific products across geo-economic areas over 1996-2008*

Year	*China*		*Europe*		*Japan*		*South Korea*		*USA-Canada*	
	*Labs**	*Scientific products***	*Labs**	*Scientific products***	*Labs**	*Scientific products***	*Labs**	*Scientific products***	*Labs**	*Scientific products***
1996	59	210	128	675	117	430	20	37	128	673
1997	91	312	134	856	122	483	28	51	132	700
1998	97	414	139	874	125	519	33	68	133	670
1999	105	467	137	1135	118	645	48	124	133	841
2000	113	612	142	1234	109	621	55	159	130	878
2001	115	780	144	1414	116	848	73	260	142	1294
2002	114	1185	140	2122	109	1214	82	425	149	2264
2003	112	2001	144	3404	107	1993	80	864	137	3696
2004	123	3070	148	4313	112	2836	86	1330	142	3607
2005	132	4476	143	5167	113	3607	84	1705	141	4375
2006	132	5760	147	5280	118	3780	90	2460	143	4601
2007	135	3324	147	3556	112	1834	89	1363	140	3301
2008	133	4864	151	4980	115	2534	89	2000	149	4819
Total 1996-2008	**1,461**	**27,475**	**1,844**	**35,010**	**1,493**	**21,344**	**857**	**10,846**	**1,799**	**31,719**

Note: *Academic laboratories, Government founded labs and Company labs are included.
** Scientific products are papers, proceedings, etc.

Table 3A: *Top 20 most prolific institutions in nanotechnology research in 2008*

Institutions*	**Country**	**Number of papers**
Chinese Academy of Sciences	China	326
Tsinghua University	China	224
Japan Science and Technology Agency	Japan	180
University of Tokyo	Japan	179
Peking University	China	171
National Institute of Advanced Industrial Science and Technology	Japan	166
Seoul National University	South Korea	161
Osaka University	Japan	156
University of Cambridge	UK	153
Zhejiang University	China	153
Shanghai Jiaotong University	China	150
National Institute for Materials Science Tsukuba	Japan	145
Consiglio Nazionale delle Ricerche	Italy	138
Jilin University	China	130
Northwestern University	USA	127
University of Science and Technology of China	China	126
Hanyang University	South Korea	121
Massachusetts Institute of Technology	USA	121
UC Berkeley	USA	119
Tohoku University	Japan	115

**Note*: In 2008, 35% of research institutions are in China; 30% in Japan, 15%in USA, 10 % South Korea and 10% in Europe (represented by Italy and UK)

Table 4A: *Top 20 most prolific institutions in nanotechnology research in 2002*

Institutions*	**Country**	**Number of papers**
National Institute of Advanced Industrial Science and Technology	Japan	98
Chinese Academy of Sciences	China	78
University of Tokyo	Japan	78
Massachusetts Institute of Technology	USA	77
Tsinghua University	China	76
National Institute for Materials Science Tsukuba	Japan	74
Osaka University	Japan	72
Nanjing University	China	71
University of Science and Technology of China	China	62
Tokyo Institute of Technology	Japan	61
UC Berkeley	USA	60
Tohoku University	Japan	58
Georgia Institute of Technology	USA	58
University of Cambridge	UK	51
Seoul National University	South Korea	50
CNRS - Centre National de la Recherche Scientifique	France	49
Kyoto University	Japan	49
Argonne National Laboratory	USA	45
Oak Ridge National Laboratory	USA	45
Consiglio Nazionale delle Ricerche	Italy	44

**Note*: 35% of research institutions in 2002 are in Japan; 25% in USA; 20% in China; 15 % in Europe (represented by Italy, UK and France) and 5% in South Korea.

Table 5A: Top *20 most prolific institutions in nanotechnology research in 1996*

Institutions*	**Country**	**Number of papers**
Naval Research Laboratory	USA	40
Osaka University	Japan	36
Academia Sinica Taiwan	Taiwan (China)	32
Institute for Materials Research, Tohoku University	Japan	31
University of Tokyo	Japan	23
Tohoku University	Japan	22
Massachusetts Institute of Technology	USA	22
CNRS Centre National de la Recherche Scientifique	France	20
Max Planck Institute for Metals Research	Germany	20
Tokyo Institute of Technology	Japan	19
University of Tsukuba	Japan	18
Pennsylvania State University	USA	18
Nanjing University	China	17
Hitachi, Ltd.	Japan	17
National Institute of Standards and Technology	USA	17
Oak Ridge National Laboratory	USA	17
Leibniz Institut fur Festkorper und Werkstoffforschung Dresden	Germany	15
Jilin University	China	14
Peking University	China	14
University of Science and Technology of China	China	14

**Note*: 35% of research institutions in 1996 are in Japan; 25% in USA, 25%in China, 15% in Europe (represented by France and Germany)

Table 6A: *Distribution % of nanotechnology studies per macro subject area and geo-economic regions*

	1996		2002		2008	
Country/ macro subject areas	*Scientific products*	%	*Scientific products*	%	*Scientific products*	%
China						
Physics and Earth Sciences	95	*25.40*	508	*21.50*	7172	*19.52*
Chemistry and Medicine	25	*6.68*	565	*23.91*	10113	*27.52*
Engineering	58	*15.51*	260	*11.00*	5667	*15.42*
Material Science	196	*52.41*	1030	*43.59*	13791	*37.53*
Europe						
Physics and Earth Sciences	419	*29.55*	1796	*29.75*	18893	*26.94*
Chemistry and Medicine	239	*16.85*	1562	*25.87*	19572	*27.91*
Engineering	171	*12.06*	719	*11.91*	10444	*14.89*
Material Science	589	*41.54*	1960	*32.47*	21212	*30.25*
Japan						
Physics and Earth Sciences	192	*32.21*	666	*31.50*	6901	*27.83*
Chemistry and Medicine	64	*10.74*	494	*23.37*	5892	*23.76*
Engineering	108	*18.12*	232	*10.97*	4814	*19.42*
Material Science	232	*38.93*	722	*34.15*	7186	*28.98*
South Korea						
Physics and Earth Sciences	16	*25.40*	191	*23.18*	2790	*21.75*
Chemistry and Medicine	5	*7.94*	180	*21.84*	3284	*25.61*
Engineering	10	*15.87*	88	*10.68*	2301	*17.94*
Material Science	32	*50.79*	365	*44.30*	4450	*34.70*
USA-Canada						
Physics and Earth Sciences	240	*25.18*	1166	*25.16*	10116	*20.91*
Chemistry and Medicine	126	*13.22*	1315	*28.37*	14789	*30.56*
Engineering	156	*16.37*	781	*16.85*	9979	*20.62*
Material Science	431	*45.23*	1373	*29.62*	13505	*27.91*
Five countries						
Physics and Earth Sciences	962	*28.26*	4327	*27.09*	45872	*23.78*
Chemistry and Medicine	459	*13.48*	4116	*25.77*	53650	*27.82*
Engineering	503	*14.78*	2080	*13.02*	33205	*17.22*
Material Science	1480	*43.48*	5450	*34.12*	60144	*31.18*

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