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Designing foresight studies for Nanoscience and Nanotechnology (NST) future developments

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Abstract

Nanoscience and Nanotechnology (NST) is widely considered as one of the most promising areas of scientific and technological development for future decades. As a consequence, almost every country in the world has chosen to invest significantly in this area. This choice, however, is only a first step in the investment decision process, given that almost any scientific discipline can be taken at the scale of a nanometre. In this paper, it is argued that foresight studies to decide where to invest in the nanotechnology area should be designed in a different way from what is normally done. Nanotechnology, in fact, has specific characteristics that should be taken into account when evaluating its expected impacts and potentialities.

Keywords: Nanoscience; Nanotechnology; Foresight process; Foresight methodology; Quantitative analyses

1. Introduction

During the last few decades, there has been increasing interest in science and technology at the nanometre scale. Significant resources are being invested in this direction by governmental institutions, public research centres, universities and firms throughout the world. At the same time, nanotechnology is still at an early stage of development and future scientific and technological results are difficult to foresee and pursue, given the broad extent of the disciplines involved and the possible technological advancements. In this context,

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foresight methodologies can play a pivotal role by individuating, inside this wide spectrum of nano-research, the most promising fields of enquiry and exploitation for nations, firms, research centres etc.

Although it is widely agreed that emerging technologies like nanotechnology, biotechnology etc., will have increasing socio-economic impacts, there are significant boundaries in terms of available economic resources and social and political accountability ("value for money") [1]. This has led to the necessity of setting research priorities not only at a macro-level (e.g. choosing between broad fields like biotechnology, nanotechnology, ICT, etc.), but also at a lower level, especially for fields that encompass many different subfields as is the case of nanotechnology. The individuation of research priorities through foresight studies [2], together with an analysis of the strengths and weaknesses of the actors involved, is paramount for increasing global economy competition. While foresight studies to identify research priorities at a macro-level are widely diffused and in many cases lead to similar conclusions in terms of macro-fields, studies aimed at understanding where to focus the efforts within these macro-fields are less developed. This instead is especially important for nanotechnology because: a) almost every country in the world has decided to invest significantly in this area, b) this decision is only a first step, given that almost any scientific discipline can be studied at the nanometre scale with new and interesting effects. The term 'nanotechnology' in fact encompasses such a wide range of tools, techniques and potential applications that some feel if is more appropriate to refer to 'nanotechnologies' [3].

In this paper it is argued that foresight studies to decide where to invest in the nanotechnology area should be designed in a different way from what normally happens in terms of methodologies and tools as nanotechnology has specific characteristics that should be taken into account when evaluating its expected impacts and potentialities.

In the first part of this paper, after underlining the importance and the development of nanotechnology, the main peculiarities of nanotechnology are presented. In the second part, the main decisional variables involved when preparing foresight studies are highlighted on the basis of the most recent literature and studies. In the final part, the peculiarities of nanotechnology are considered as the driving elements for the design of a new approach for foresight studies for this area.

2. NST and its peculiarities

The beginning of the path which has led to what is now called "nanotechnology" is usually traced back to a famous lecture proposed by the 1965 Physics Nobel Prize winner, Richard P. Feynman, who, in 1959, explained to the world that "There's plenty of room at the bottom" [4]. Feynman's ideas concentrated on the absence of any intrinsic physical limitation to scaling down to the manipulation of the single atom. More than 20 years later, a group of researchers at IBM in Zurich presented the first apparatus capable of "seeing" and manipulating a single atom: the Scanning Tunnelling Microscope (STM) [5] which was followed, a few years later, by the Atomic Force Microscope (AFM) [6]. These tools paved the way to what was once considered utopian, but is now regarded throughout the world as "the next big thing".

As is now widely recognized, NST does not merely concern with extreme miniaturization. It is now possible to say that "conceptually, nanotechnology refers to science and technology at the nanoscale of atoms and molecules, and to the scientific principles and new properties that can be understood and mastered when operating in this domain. Such properties can then be observed and exploited at the micro- or macro-scale, for example, for the development of materials and devices with novel functions and performance" [7].

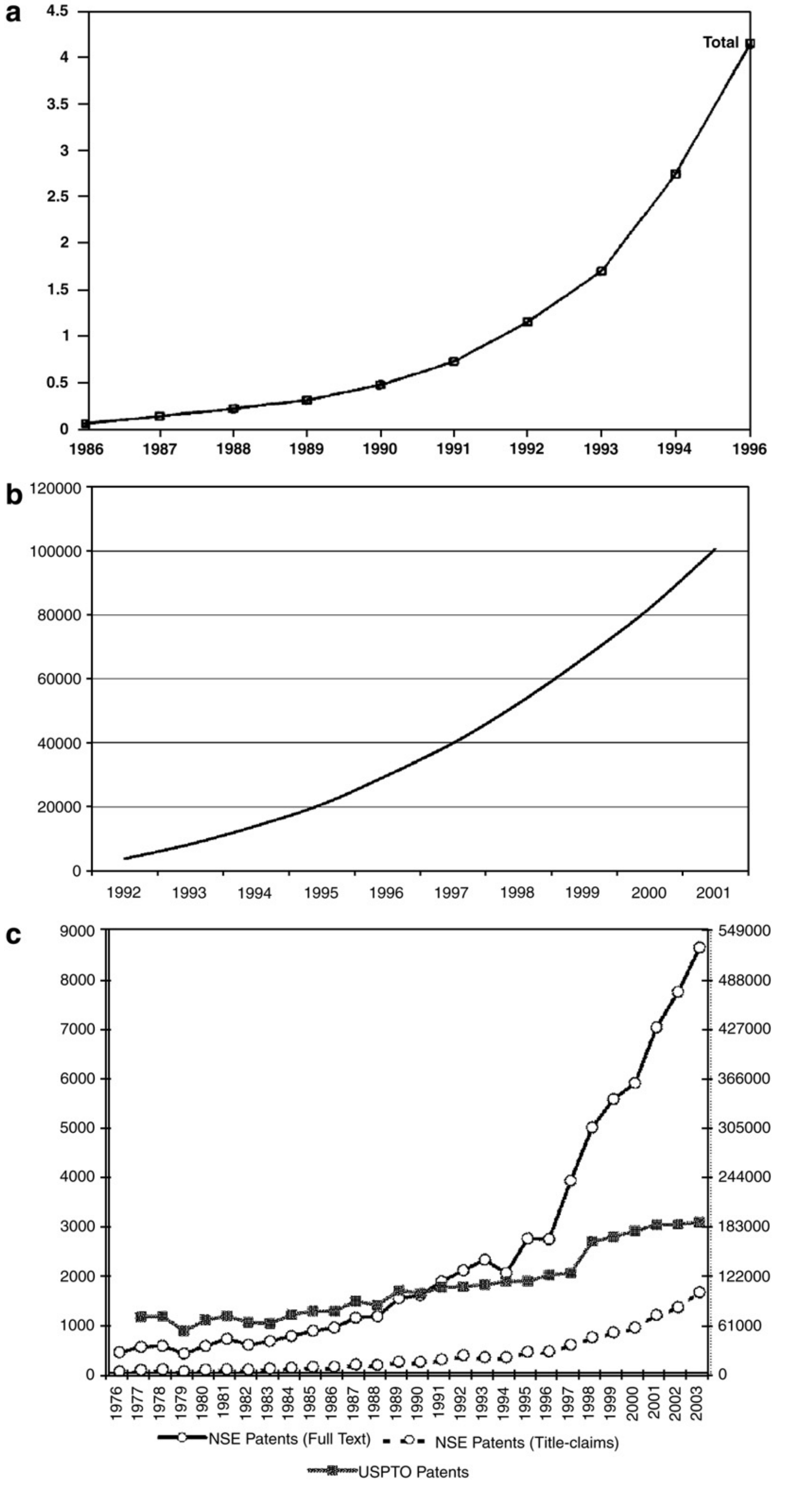
a
Total
1986
1987
1988
1989
1990
1991
1992
1993
1994
1996
b
1992
1993
1994
1995
1996
1997
1998
1999
2000
2001
c
NSE Patents (Full Text)
NSE Patents (Title-claims)
USPTO Patents

Table 1a
Nanotechnology funding (million $, 1€=1$)

	1997	1998	1999	2000	2001	2002	2003	2004
Europe	129.6[a] (23)	139.8[a] (26)	164.7[a] (27)	184[a] (29)	–*(225)[b]	–*	1150[e] (350)	–*
USA	116[b]	190[b]	255[b]	270[b]	465[b]	653[b]	862[c]	961[c]
Japan	120[b]	135[b]	157[b]	245[b]	670[d]	713[d]	753[d]	783[d]

Public expenditure reported for Europe includes countries like Switzerland. Moreover public expenditure is constituted by the national programme expenditure and European Commission budget. The total amount of money invested in nanotechnology is reported and, in brackets, the amount of money allocated by the European Commission.
Data sources: a. [11]; b. [14]; c. National Nanotechnology Initiative website (http://www.nano.gov); d. [12] [13]; e. [7]; *data not available.

2.1. Nanotechnology development and financial efforts

The developments of NST over the last 20 years have been quite striking and evidence from patent and publication data, taken as proxies of scientific and technological development of the "nano-world", clearly show the interest and flurry of activity concerning this topic.

The growth rate of "nano-title-papers" over the 1986–1995 period, followed an exponential law [8] with a doubling time of 1.6 years (Fig. 1a), while a more recent research [9] in the 1992–2001 ten year period, conducted with a more advanced search strategy and a larger coverage database, found an exponential law for the growth rate in publications, but a lower doubling time of 2 years (Fig. 1b).

Even the evolution of patent submission (Fig. 1c) shows that technological exploitation is one of the main tasks of nanotechnologists [10].

As far as such scientific and technological efforts are concerned, almost every country in the world has already undertaken national programmes, or will soon do so, in order to support fundamental research as well as technological exploitation of the results in the field of nanotechnology.

The funding activities in Europe, based upon governmental data [11–14], both via the European Commission and the National Governments, USA, that have led to the creation of the National Nanotechnology Initiative in 2000, and Japan are reported in Table 1a.

Apart from these major competitors in the field, many other countries are currently investing heavily in nanotechnology. For instance, South Korea has planned to make public investments for a total of 819 million dollars (which will become 1237.5 million dollars if private interventions are considered) from 2001 to 2010 [15], Australia, is investing 100 million dollars per year in nanotechnology (more than half of which is public) and is now asking for a national initiative that is capable of capitalising opportunities and competencies in the country [16], Taiwan has devoted 600 million dollars over 6 years [7] and even Eastern European countries [17] and China [18] are active protagonists in the worldwide race for nanotechnology leadership.

The European Community and the USA have pledging to increase financial support for nanotechnology in the next few years. Europe has assigned 4.865 billion euros for "Nanosciences, Nanotechnologies, Materials and new Production Technologies" in the draft of the 7th Framework Programme for the 2007–2013 period [19]. The United States, with an act dedicated to Nanotechnology [20], established 3.679 billion dollars for

Fig. 1. (a) Number of "nano-title-papers" (thousands) per year from 1986 to 1995 [8]. (b). Number of "nano-title-papers" per year from 1992 to 2001 [9]. (c). Number of "nano-patents" per year from 1976 to 2003 [10].

Table 1b
Estimate of nanotechnology funding in the 7th Framework Programme of the European Community (our elaboration from [19])

Year	2007	2008	2009	2010	2011	2012	2013
Funds for nanotechnology (million €)	340.5	486.5	583.8	690.8	822.19	909.8	1031.38

NSF, DoE, NASA, NIST and EPA (funding for defence was not included) for the 2005–2008 period. A rough partition of European funding over the different years, based on the relative weight that different years have had on the partition of the total amount of money for the "Cooperation" action in the 7th Framework Programme is presented in Table 1b, while the budget for nanotechnology in the US for the 2005–2008 period according to the 2003 act is reported in Table 1c.

2.2. NST peculiarities and implications

Through a literature analysis, interviews with leading researchers and our own studies in the field we have identified four peculiarities that distinguish NST from other scientific and technological fields and which play a critical role in the design and execution of a foresight study on NST. The first two (*interdisciplinarity* and *pervasiveness*), in particular, are deeply rooted in the nature of Nanoscience and Nanotechnology, while the last two (*early stage* and *spread throughout the world*) pertain to the context in which NST has emerged and developed over these years.

2.2.1. Interdisciplinarity

The particular length scale, the nanometre, namely one billionth of a meter, brings human understanding capabilities to that point of view where all disciplines in natural sciences merge, that is, the atomic and molecular point of view. All inanimate objects as well as living beings consist of atoms and molecules: in this sense there is no conceptual difference if we talk about nerve cells, DNA filaments, buckyballs or titanium particles. Nanotechnology offers the chance to understand and engineer at a molecular scale, no matter what the molecule is. For instance, a great convergence is expected in electronic devices, photonic devices, sensors etc., as depicted in Fig. 2.

For this reason nanotechnology is essentially regarded as being characterized by interdisciplinarity, i.e. by an interaction and cross-fertilisation between different disciplines, a more radical process than multi-disciplinarity, which involves the interest and involvement of different disciplines in such a new approach, according to Schummer's clarification [21].

Multidisciplinarity, in fact, has been greatly increased by the diffusion of tools such as the STM and the AFM, which gave rise to nanoscale microscopy studies and applications in physics, materials science, engineering, biology and medicine. Interdisciplinarity, namely the mergence, or at least the collaboration, between previously separated fields, is instead only in its infancy. Surface science, which is closely related

Table 1c
US Nanotechnology funding for the 2005–2008 period (our elaboration from [20])

Year	2005	2006	2007	2008
Funds for nanotechnology (million $)	809.8	889.55	955.41	1024.1

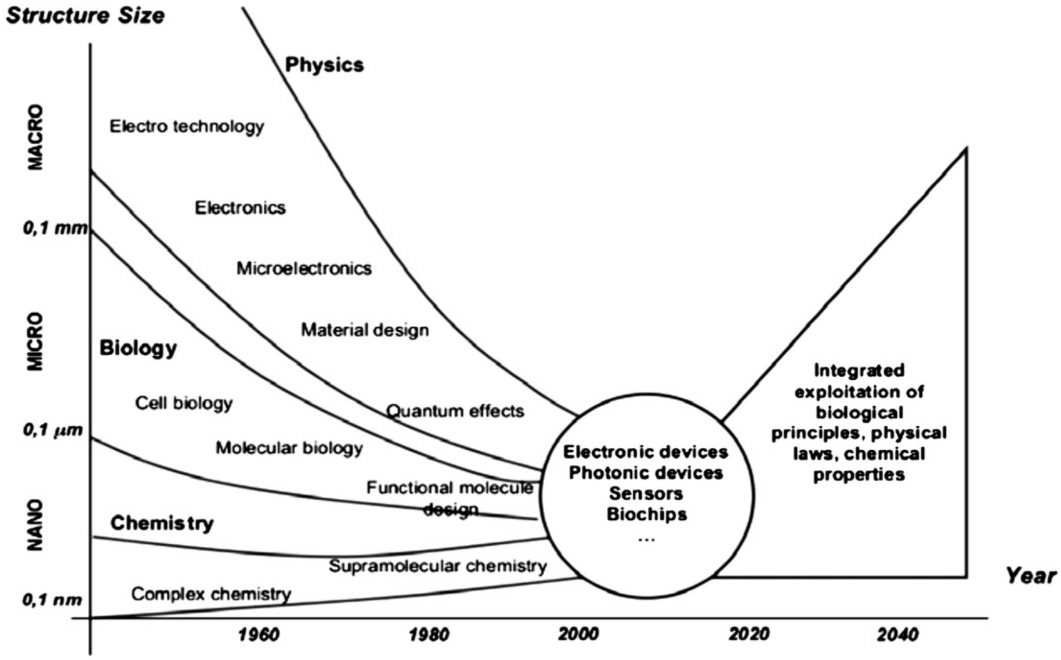

Fig. 2. Convergence at the nanoscale (source: VDI Technology Centre, Future Technology Division).

to nanotechnology (whose typical objects are characterized by a high surface–volume ratio), is an example of such a phenomenon which represents a meeting point for physics, chemistry and materials science.

Nanotechnology should be regarded as essentially interdisciplinary as its typical length scale probes at the overlaps and boundaries of many traditionally separated disciplines half-revealing the chance of many possible and desirable (and sometimes fearful) effects.

For this reason almost every report, paper and recommendation concerning policies for NST development, claims to introduce measures for the creation of interdisciplinary research teams and infrastructures as well as a new approach in education and training for the introduction of interdisciplinary curricula, even in the secondary school [22–25].

The high degree of complexity which requires an increasing level of specialization and a formal division of labour, the increasing cost of fundamental research coupled with the gradually enclosing boundaries of previously separated disciplines are good reasons to encourage and foresee research collaboration which can “bring about a clash of views, a cross-fertilisation of ideas which may in turn generate new insights or perspectives that individuals, working on their own, would not have grasped (or grasped as quickly)… collaboration is greater than the sum of its parts. Such benefits are likely to be largest when the collaboration involves partners from more divergent scientific backgrounds.” [26].

Therefore, interdisciplinarity can be considered as a proper feature of nanotechnology that must be encouraged. Moreover, a measure of the degree of interdisciplinarity can, and actually should, become a parameter for the evaluation of the overall success for policies for nanotechnology, although it is difficult to define and obtain [27].

In this respect it could be useful to note the increasing interest in "Converging Technologies" [28], i.e. "enabling technologies and knowledge systems that enable each other in the pursuit of a common goal" [29]. Four areas of human knowledge, Nanotechnology, Biotechnology, Information Technology and Cognitive Science, should realize this convergence by merging together to strengthen and amplify human capabilities and social relationship. This growing discipline, sometimes called NBIC (sketched in Fig. 3), is now regarded as the most promising field of knowledge over a very long timescale.

2.2.2. Pervasiveness

The new knowledge created by the mergence, at a nanoscale, of disciplines which were previously separate, results in real and potential applications in many different fields.

Many institutions have tried to understand the fields that are most affected by the massive introduction of nanotechnology. On the basis of the European Commission [7] and the United States National Nanotechnology Initiative documents [30], it is possible, for example, to extract a list of R&D areas in which nanotechnology can/will play a key role.

This list can be summarized as follows:

1. materials science (characterization, materials by design, functionalization);
2. medical applications (diagnostic and therapeutic);
3. nano-electronics (-photonics, -magnetism) and, in a broader sense, information elaboration processes;
4. energy production and storage;
5. metrology and development of instruments;
6. food, water and environment;
7. manufacturing processes;
8. security (both passive and active);
9. robotics.

If we look at this list, and analyse patent data [10] and the first applications which exploit nanotechnology principles and results, it is reasonable to think that very few aspects of human life will not be touched by this "revolution". This explains why nanotechnology is considered as a key element in the transition to a knowledge-based economy and justifies the huge amount of money (and the high incremental rate) that

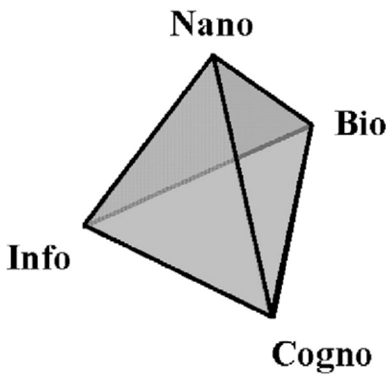

Fig. 3. The NBIC tetrahedron (adapted from [28]).

governments are investing in the hope of playing a primary role in the field to gain competitive advantages for their industries.

2.2.3. Early stage

In spite of more than 20 years of significant efforts, NST can be considered as being in the early stage of its scientific development and technological exploitation. As a result of the previously listed features (interdisciplinarity and pervasiveness) there is no discipline or set of disciplines with well defined borders. Moreover, the traditional disciplines (i.e. physics, biology, chemistry, engineering) involved in the scaling down to the nanometre are encountering difficulties in finding and mastering new properties and principles and in interacting with each other as new common languages and tools are required. Finally, nanotechnology-based development and innovation have to face many difficulties in scaling up to volumes and lean times that are compatible with industrial processes and batch production, and many dangers related to social and ethical concerns will have to be faced on this road to mass production and distribution.

2.2.4. Spread throughout the world

Contemporarily to the increase in NST, the phenomenon of globalization has taken place together with a new means of communication. The easier movement of people from one country to another and the great interest of many governments in playing a primary role in these disciplines have contributed to a worldwide distribution of knowledge and competencies.

Contrary to what happened in the past, to those that can be considered the last important techno-scientific revolutions, i.e. the development and growth of microelectronics and biotechnology, no hub or cluster can be seen for this discipline. There is no *Silicon Valley*, or a *Cambridge* for nanotechnology yet: this delocalization of knowledge requires an empowered capacity to find competencies, as will be clearer in the following.

2.2.5. Implications of NST interdisciplinarity and pervasiveness

According to Dosi a *technological paradigm* can broadly be defined “in accordance with the epistemological definition as an ‘outlook’, a set of procedures, a definition of the “relevant” problems and of the specific knowledge related to their solution. We shall argue also that each ‘technological paradigm’ defines its own concept of ‘progress’ based on its specific technological and economic trade-offs.” [31]. In this sense, nanotechnology is expected to introduce more than one technological paradigm and in its meaning of “outlook” it can already be considered as a technological paradigm, which generates efforts and expectations.

As the range of implications NST could have is the widest, many studies and funds have been directed towards a correct comprehension of the perceived opportunities and threats that can influence the acceptance of the massive introduction of nanotechnology-based products [3,29,32–34].

Such implications will be observed mainly in four dimensions: science, technology, society and economy, as summarized in Table 2.

Some of the main implications that nanotechnology will bring in the future in particular concern:

- knowledge:
  - easy access and intelligibility of the established knowledge of disciplines at the borders of which nanotechnology grows;

Table 2
Impacts of NST features on science, technology, society and economy

		Impact dimensions			
		Science	Technology	Society	Economy
Nanoscience and nanotechnology peculiarities	Knowledge production (interdisciplinarity)	Knowledge, language, infrastructures	Tools, infrastructures	Education, labour organization	Infrastructures, tools, regulation impacts
	Technological exploitation (pervasiveness)	New process fundamentals	Fusion of previously separated industrial sectors regulation impacts	Ethical, legal, health concerns. Effects of integration and convergence	Impacts on market, business, organization, management

  - construction of a common language;
  - creation and production of new experimental tools, to strengthen and expand nano-metrology;
  - creation of infrastructures that are capable of supporting interdisciplinarity;
- manufacturing:
  - new principles and fundamentals that can change traditional processes;
  - overlapping and fusion of previously separated industrial sectors;
  - modifications in labour organization;
- privacy: miniaturization and widespread diffusion of communication devices and sensors;
- health: effects of nanometric particle interaction with human tissues and organs;
- ethics: manipulation of matter at a nanoscale, especially human cells;
- environment: diffusion of nano-waste;
- regulations: standards, safety regulations, intellectual property rights;
- education: organizational and content changes in courses and programmes to prepare a new generation of skilled workers;
- economic disparity: exclusion of poor countries from benefits;
- cultural threats: due to radical changes in personal habits and behaviour.

There are at least three reasons for undertaking and sponsoring studies which aim at giving insights in the implications of nanotechnology. First, the announced advantages, which are claimed almost daily, and the future developments have to face a doubtful attitude that in recent years has arisen in the public opinion towards radical and fast changes introduced by scientific and technological development. In particular, in the last few years, we witnessed two of these phenomena: the dotcom bubble, which represented the possibility of a financial failure due to an over-estimation (and speculation) of new technology chances and the GMOs, which showed the power, and the influence, of public opinion in determining success or failure of an innovation.

Furthermore, when building nano-devices, worries can arise because these objects cannot be seen or detected. Public and governmental attention to this kind of problem is increasing and this requires the involvement of scholars and experts in assessment and foresight activities.

Finally, society has to be prepared for the changes that NST will entail, both as prerequisites for its development and as consequences of its introduction.

3. Foresight methodologies

An attempt to make predictions is intimately connected to the human capability and need to make projects and plans. This is even more the case when speaking about economic and political matters where planning is something more than just a wish. Organizations and governments that are supposed to take decisions that will affect many lives, economic systems and international relations must consider the ability to make reliable outlooks as a vital requirement.

Science and technology, with the related matters and implications for research, industry, economy and society, are among the main fields over which the development and the application of methodologies for future forecasts have ranged over time, as can be seen by looking at the beginning of Project RAND launched at the end of World War II on the basis of such a consideration: "During this war the Army, Army Air Forces, and the Navy have made unprecedented use of scientific and industrial resources. The conclusion is inescapable that we have not yet established the balance necessary to insure the continuance of teamwork among the military, other government agencies, industry, and the universities. Scientific planning must be years in advance of the actual research and development work" (December 1945, report to the Secretary of War of the Commanding General of the U.S. Army Air Force, H.H. "Hap" Arnold).

Many of these methodologies that have been developed in the last 60 years are reviewed in literature [35,36]. Among these, Technology Foresight has acquired a primary role as a "systematic, participatory, future intelligence gathering and medium-to-long-term vision building process aimed at present-day decisions and mobilising joint actions" characterized by *anticipation* of long-term social, economic and technological developments and needs, *participation* of a wide variety of stakeholders, creation of new *networks*, elaboration of a strategic *vision* and transfer of results into *actions* [37]. Such results are reached by laying stress on a process characterized by "the five C's": Communication, Concentration, Coordination, Consensus, Commitment [2].

Luke Georghiou has traced a trajectory for Technology Foresight across its applications over the years. Differences can be determined over a small set of dimensions and allow three different Technology Foresight generations [38], which can be summed up as in Table 3, to be described.

Table 3
Foresight generations (adapted from [38])

	Aim of the exercise	Actors involved	Panel formation and surveys	Economic rationales	Evaluation criteria
1st generation	Technology forecasts	Technology experts or professional futurologists	Follows disciplinary taxonomy	Economic planning	Accuracy of predictions and diffusion of results
2nd generation	Technology and market	Academia and industry (those spanning the gap)	Structured in terms of industrial and service sectors	Market perspective, with market failure	Extent to which priorities have been considered and formation of networks
3rd generation	Technology, market and societal issues	Inclusion of social stakeholders and government× representatives	Thematic structure, socio-economic problem solving oriented	System failure: foresight bridges the socio-economic gap	Broad networks (with social stakeholders) and foresight culture establishment

Table 4
Scope issues of a Future Technology Analysis [36]

Content issues
Time horizon
Geographical extent
Level of detail: micro (company), meso (sector), macro (national, global)

Process issues
Participants (number, nature, disciplinary mix)
Decision processes (operational, strategic, visionary)
Study duration
Resources available (funding, data, skills)
Methods used (data needed, analytical outputs)
Organization (process management)
Communication flows (internal, external, nature of participation)
Representation of findings (technology information products, usability)

Though restricting future analysis methods to Technology Foresight there are still a certain number of techniques that can be distinguished on the basis of 4 axis [37], for example: top down–bottom up approach (which is related to formal products–learning processes orientation), exploratory–normative, quantitative–qualitative, expert-based–assumption-based. On the other hand, A.L. Porter, and the working group he led, tried to point out the general features of a Technology Future Analysis by dividing them into *Content Issues* and *Process Issues*, which are summed up in Table 4 [36].

Another peculiarity of foresight studies pertains to the relationship between the absolute value of possible alternative investigated futures, i.e. a particular development of a technology, and its practicability in terms of real introduction into a certain scientific, industrial and social environment. This difference is addressed by talking about attractiveness and feasibility. Therefore, as we are dealing with S&T opportunities, we cannot ignore the fact that the command of a technology, though absolutely attractive, necessarily undergoes the concurrence of a set of particular conditions that makes it feasible (related industries, infrastructures, skilled labour, etc. etc.).

International literature reports many examples of Technology Foresight exercises that address different aims, territorial needs, outputs and the results attained [37,39–41].

Although interest in NST scenarios goes back to the very first years of their development [42], NST is mentioned in the majority of the foresight exercises as a monolithic discipline treated as a whole with respect to other fields and sectors (i.e. health, information technology, manufacturing…) and in competition with them. Moreover, some of these foresight exercises do not mention nanotechnology explicitly and consider traditional categories whose future developments can be related to nanotechnology [43].

On the other hand, in recent years, NST has been investigated as a branched discipline considering its full spectrum of complexity [44–46] or deepening one particular field of development and application [47,48].

Finally, a particular institution, the Micro and Nanotechnology Commercialization Education Foundation (MANCEF), led a roadmapping project named “the International Industrial Microsystems and Top-Down Nanosystems Roadmap” (IIMTDNR) [49] and roadmapping, in general, could be a viable approach for disruptive technologies, as NST is, in order to steer the sudden and radical changes it causes [50].

Novelties in science and technology as well as in investigation instruments give rise to new challenges and needs, which Technology Future Analysis will have to face [36]. Some of these are closely related to nanotechnology and therefore to the aim of this paper. They can be set out as follows:

1. Convergence towards common scientific issues among traditionally separated disciplines (physics, chemistry and biology, for example) leads to great challenges for established knowledge (as far as technology, science and philosophy are concerned) which implies the creation of new organizational and structural matters;
2. A more profound knowledge of the building blocks of nature can enable us to think of the possibility of achieving made-to-order solutions for the problem that has to be faced, leveraging on normative and roadmapping approaches;
3. Some industrial sectors are experimenting a transition towards a more intensive science-based core business which means that future developments can be foreseen more in the science field, i.e. fundamental properties, than in technological applications.

In a broader sense, anticipatory studies are going to face, and in many cases are already facing, a new era of innovation processes led by two driving forces: miniaturization, or rather the capability of mastering the matter at the atomic and molecular scale, and convergence, favoured by information technologies and miniaturization itself. These phenomena lead to a shift from technology to science-based innovation with the creation of completely new industries and the introduction of radical changes in the traditional ones.

NST is at the centre of these processes and thus both significantly influences them and is influenced by them.

In this new scenario, forecasts become more difficult as attention moves from technological development to scientific research, which is intrinsically oriented to the long-term horizon and is not focused on immediate industrialization or product innovation: a new era of technology forecasting "defined by the focus on the molecular level, with nanotechnology, biotechnology and materials science coming to the fore" [51].

This shift from technology to science-based innovation increases forecasting complexity and lowers predictive capability. For these reasons, methodologies coming from or inspired by disciplines traditionally related to high degrees of complexity (i.e. biology, genetics, natural sciences) and quantitative data find new applications in forecasting emergence and innovation, like the evolutionary theory [52], neural networks [53], cellular automata [54] genetic algorithms [55] and complex adaptive systems [56]. These new *biology-based forecasting methods* are not dealt with in depth in this paper, but some more considerations regarding a quantitative approach to forecasting in general have been added to the following paragraph.

3.1. Quantitative contributions

The use of quantitative methodologies in technology foresight is often due to a demand for objectiveness and a greater comparability of results, despite the necessarily simplified description of the phenomena, especially those related to society, and, frequently, with underlying assumptions about the relationships among the variables and about the conservation of present conditions for the future.

Nevertheless, a strong tendency towards the use of quantitative methods to inform strategic decisions in S&T policy matters is becoming established. When talking about quantitative methods, we mainly refer to bibliometric approaches and patent analysis. These tools fit multiple needs: the assessment of institutions or policy measures [57,58], the detection of points of excellence and planning in promising fields or problematic areas [59]. Furthermore, the reiterated use of these instruments can offer snapshots of the situation at different moments of time to help build up time-series that can enable forecasts for the future [60].

Such informative aptitude together with the ability to synthesise, which is typical of quantitative (and statistical) tools, can supply crucial support for foresight activities concerning nanotechnology. While describing and listing methods used to gain insight into the possible developments of technology, the Technology Future Analysis (TFA) Methods Working Group noticed that information technology gives new perspectives to future analysis that are mainly connected to: a. the existence and the organization of complex networks, b. simulation modelling techniques (especially for complex adaptive systems) and c. the existence and search techniques of vast databases [36]. Moreover, as previously mentioned, nanotechnology is in the early stages of development, is intrinsically interdisciplinary and is characterized by widespread knowledge. Therefore these methods can be regarded as a precious contribution to the investigations on NST development.

An example of the use of quantitative methods applied to nanotechnology is given by the attempt to quantify the expansion, first, and then the degree of multidisciplinarity and interdisciplinarity of this new science and technology, moving from the bibliometric approach [8]. Though interdisciplinarity is a proper feature of NST, as already mentioned, there is no general agreement, even for methodological reasons, about a reliable measurement of this feature in nanotechnology [21,61,62].

Indicators related to publications and patents can also be used to map the field by analysing its structure in terms of scientific and technological domains and their development in time as well as the patterns of collaboration and excellence (research groups, institutions, regions, countries) [9,10,63] or to support decision-maker choices via the depiction of scenarios for nanotechnology evolution and a future based upon the analysis of its stage of maturity [64].

This kind of quantitative instrument can perform the task of supplying a correct framework of the players involved in the field, as well as their particular capabilities and competencies and their links with other players. The possibility of using these instruments in large databases that summarise enormous amounts of data in indicators or maps can give synthetic information about the NST state, a sort of "nano-at-a-glance", which is always useful for a quite new and rapidly changing field. Finally, quantitative tools can meet the demand for a detailed insight into this discipline with an appropriate employment of resources.

4. Designing foresight studies for future Nanoscience and Nanotechnology developments

In this section, nanotechnology peculiarities are crossed with typical Technology Foresight dimensions to show that foresight studies, in order to decide where to invest in the nanotechnology area, should be designed in a different way from the one normally used and to identify the characteristics of a new approach to foresight studies for this area.

4.1. A new approach for NST foresight studies

A possible model for an analysis on the future of nanoscience and nanotechnology must take into consideration the peculiarities that such a field presents at the moment.

As described in Section 2.2, four aspects can be underlined:

- NST is in the early stages of development. Although it is almost 20 years since scientific and technological discoveries related to the field first appeared and despite the promises they are making, the path to a wide employment and diffusion in industrial processes and in end consumers' products seems to be long and rough.

- The creation of new knowledge in the field, in terms of scientific discoveries and technological inventions, is from all over the world with an increasing role being played by non-traditional far-eastern countries such as China and Korea. Both financial and bibliometric data concerning nano-R&D support the vision of a global competitive scenario.
- Up to now, NST has arisen and developed at the borders of many different disciplines. Interdisciplinarity is the main scientific peculiarity of NST, which will perhaps generate many different, separate and new disciplines in the future which are now aggregated together in the term "nanoscience" or "nanotechnologies".
- The possible generation of discoveries, inventions or paradigms that affect many branches of technology and many fields of human activities makes NST potentially pervasive in a number of industrial sectors.

As already noted, the first two peculiarities are well rooted in NST, while the last two do not depend on the nature of NST, but on the context in which they emerged. In this sense, other disciplines may share these contextual variables with NST. Nevertheless, as will be even clearer in the following, their impact on the design of foresight studies cannot be omitted either. When dealing with the problem of designing, preparing and carrying out a foresight study on NST, all its peculiarities play important roles.

First of all, considering NST as an early stage discipline and technology enlarges the timescale over which we can obtain solid scientific discoveries, technological developments and innovations and social and economic impacts. Secondly, the spread of knowledge and the delocalization of centres of competences, requires sources and information retrieval methods which could make it possible to draw up worldwide competence maps in NST. Furthermore, the challenge connected to interdisciplinarity is three-fold: the identification of the disciplines involved, the localization of the correct set of people who could eventually be involved in expert-based studies, the evolution of a proper interdisciplinary language which could have an impact on the retrieval of new information and consequently on the comprehension of the phenomena. Moreover, the peculiarities concerning the early stages of development, worldwide diffusion and interdisciplinarity require powerful instruments to trace the emergence of scientific research and its outputs throughout the four corners of the earth. Finally, NST pervasiveness requires particular attention to identify all the correct stakeholders for each application that can be useful in foresight studies to elaborate the impacts and effects, especially because the same discovery, or invention, could result in different applications, each of which would be characterized by its own stakeholders.

What has been stated above makes it possible to point out which typical dimensions of a foresight study are affected by NST peculiarities and therefore need particular attention in the design phase and in execution. Such Foresight Issues, both from the already presented Content and Process Issues (Section 3), are:

- Time horizon;
- Geographical extent;
- Use of quantitative data (which is related both to the available resources and to the methods used, see Table 4);
- Participants in panels, expert workgroups, surveys.

Crossing these Foresight Issues with NST peculiarities introduces a new foresight approach, which is schematised in Table 5 and discussed in the following.

Table 5
Peculiarities of a foresight study on NST

NST peculiarities		Challenges and Foresight Issues involved			NST foresight studies	Traditional foresight studies
Early stage	→	Tracing scientific discoveries which potentially imply important technological developments	Time horizon	→	Mid to long-term	Short to mid-term
Spread throughout the world	→	Difficulties in concentrating on a few big players	Geographical extent	→	Essentially worldwide	Limited to territorial competencies (national or regional)
Interdisciplinarity	→	Identification of disciplines involved and the evaluation of effects of interdisciplinarity on traditional disciplines	Participants in foresight studies Available resources and Methods used	→	Experts addressing different Stakeholders' needs Relevance of the social implications and effects on peoples' lives and habits Use of database with structured techno-scientific information (see Fig. 4)	Stakeholders essentially from research institutions and industrial sectors. Limited consideration and relevance of social implications Minor contributions of quantitative data in S&T foresight studies
Pervasiveness	→	Anticipating the correct set of technological, industrial, social and economic implications of NST discoveries and inventions				

4.2. Discussion

The new approach to NST foresight studies reported in Table 5, obtained by crossing the selection of Foresight Issues that are affected by NST peculiarities with these peculiarities, has some methodological and managerial implications that are worth discussing.

4.2.1. Time horizon

The present stage of comprehension of the principles of nanoscale science and of the development and exploitation of technological devices makes it difficult to foresee considerable impacts on science and technology in the short term. A mid-term timescale (5 to 15 years) could be considered as appropriate for forecasts concerning the development of science and technology at a nanoscale in traditional (and separated) disciplines. Long-term studies (15 to 25 years) would be better to fit the needs of outlooks concerning the impacts and effects of interdisciplinarity. This second effect, i.e. the mergence of disciplines, will surely have a deeper impact than the first one, but it will take longer.

Both the mid-term and the long-term timescales should be considered for the social and economic impacts. In the mid-term, it is possible to evaluate the impacts of the requirements and needs of nanotechnology development (such as assigning investments, building infrastructures, introducing regulations, launching research and education policies, etc.), while, in the long-term, the effects of the massive introduction of nanotechnology into society and economy can be foreseen.

4.2.2. Geographical extent

The strategic relevance generally attributed to nanotechnology, the subsequent launch of national and international programmes and the general interest of international scientific communities have established the premises for the creation of an absolutely non-localized nano-community. This is the reason for considering a worldwide scale when investigating the attractiveness, the state of development and the competencies of particular technologies within the nano-world. As far as the economic and social dimensions are concerned, the global horizon should be considered a general framework in which the local forecasts can be located: this is consistent with the local nature of social and economic impacts, while global outlooks could be useful to find similar situations, to anticipate possible troubles and to grasp innovative solutions. When we use the term “local” we are referring to the territory over which the proponents’ authority is effective or where proponents’ decisions have an effect.

4.2.3. Use of quantitative data

The evaluation of impacts related to the scientific and technological dimensions of nanotechnology can benefit, as previously mentioned, from the use of quantitative methodologies with particular attention to the bibliometric analyses of publications and patents and biology-based forecasting methods. Such analyses, which can meet the need for a synthetic comprehension of a knowledge branch diffused throughout the world, have multiple aims:

1. Bibliometric analysis can offer a wide overview of the field with the relative dimensions and importance of the subfields, together with an evaluation of the best worldwide players in the field (and for each subfield)
2. Patent analysis can identify the most active areas from the point of view of technological exploitation; the use of co-authorship and authors’ affiliations can lead to maps and collaboration patterns that offer insights into the establishment of interdisciplinary networks and, with the help of publication citations

in patents, can show the cross-fertilisation effects and the progressive approach of traditionally separated industrial sectors

3. As a by-product, these instruments, drawing up maps of expertise and competencies, supply a really vast set of people who can be involved in interviews, panels or surveys and so on. Moreover, each map is taken in a certain moment of time: in this sense, a collection of maps at different instants could suggest the dynamics of the field with possible, and reasonable, extensions for the future.

Finally, particular attention should be paid to the analysis of the research teams which join together in order to submit project proposals to be financed. Investigating the composition of proponent teams of publicly financed projects (together with an analysis of the aims of their work) can provide interesting data concerning collaboration networks and interdisciplinarity, but it can also give a quite precise idea of the directions that excellent groups are taking, with a subsequent deduction about those outlines which can be considered as the main lines for future developments.

4.2.4. Participants in panels, expert workgroups, surveys

It is always difficult to compose panels for a Delphi exercise for the elaboration of scenarios or for any kind of study which can require the involvement of experts implicated in nanotechnology research and development. The use of quantitative data, as previously stated, can simplify the research, at least from the scientific and technological point of view. The task, however, remains difficult: 1. considering nanotechnology as an early stage technology with a great impulse towards interdisciplinarity, implies that experts must come from different disciplines that are both adjacent to each other and far from each other; 2. the multiplicity of actors affected by the impacts of nanotechnology requires the presence of representatives of each stakeholder.

4.2.5. Process implications

Taking into account the enlargement of the set of tools employed and, in particular, the important role of quantitative contributions can have significant implications on the foresight process.

In particular, the integration of traditional expert-based studies with quantitative analyses could be carried out, for instance, according to these three steps:

1. Pre-process. The team that leads the exercise selects the borders of the analyses, chooses the databases for the techno-scientific information, and structures the search key in order to collect the related documents. These operations can be carried out with the help of literature on technology management, grey literature and selected experts who could set up a scientific committee for the study, with consultation and validation tasks.
2. Quantitative analyses. The team uses the results of the pre-process phase in order to obtain information on research activities and technological development throughout the world. This phase of the process is represented in Fig. 4, with the structured information sources, the most interesting fields for each source and the results that can be obtained from the combined analysis of this information. These results are useful *per se*, but they also constitute a solid basis for the selection of experts in nanoscience and nanotechnology.
3. The phase of the experts' opinion. Finally, experts from the different stakeholders of the NST development process are gathered in order to evaluate the opportunities and the threats that arise from the massive introduction of future NST into society. Together with science and technology experts

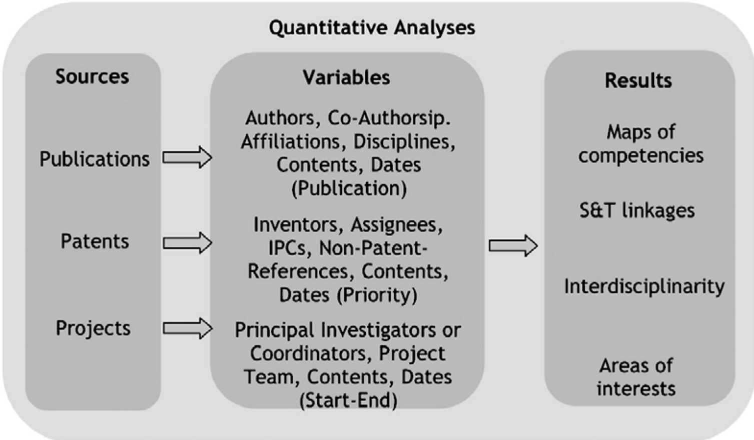

Fig. 4. Quantitative analyses in a foresight study process.

from the second phase, people from different industrial sectors, experts in economy and finance, policymakers as well as scholars and experts in social trends and society needs should be involved for the widest view of the field, due to the ample range of possible implications in everyday life in terms of privacy, security, health, bioethics and so on.

4.2.6. Managerial implication

As NST is considered one of the keystones for future competitiveness (together with biotechnology, energy and ICT and with some positive and important overlaps between them), the aim of foresight studies is to support decisions concerning the investments which have to be made in order to achieve a primary role in fundamental research and technological applications. In particular, foresight studies should help in the identification of key technologies and key players within the overall NST scenario.

Given the early stage of development of such technologies and their close relationship with fundamental research, the sponsors of these studies are normally (and in the future will probably be) governments (regional, national or supranational), industrial associations, or any entity that could be able, with proper levers, to put into action the conclusions of such studies on NST.

For these actors it is important to note that, apart from the previously made consideration, another aspect should be considered: the possibility of fully exploiting a promising area. Even when a set of promising emerging technologies (i.e. potentially disruptive) is spotted, they become key technologies only when their attractiveness, in terms of technological, economic and social development and enabling capability, is matched to their feasibility, i.e. the chances that the sponsors of the NST foresight studies have in transferring such attractiveness into actual development and progress.

5. Conclusions

Nanotechnology is widely considered as one of the most promising areas of scientific and technological development for future decades. As a consequence, almost every country throughout the world has chosen to invest significantly in this area. This choice, however, is only the first step in the investment decision process, given that almost any scientific discipline can be taken at the nanometre scale. This paper points out that foresight studies for nanotechnology (i.e. studies to chose where to focus on in the nanotechnology area) should be designed in a different way than the one normally used. In particular, it has been underlined, with reference to the most recent studies, that nanotechnology is characterised by *interdisciplinarity* and *pervasiveness* and that these characteristics should be taken into consideration when designing nanotechnology foresight exercises.

Further studies could be useful to highlight the extent of the impacts of the nanotechnology peculiarities on foresight methodologies. However, some broad issues can be recognised and they have been discussed in this paper:

- First of all quantitative methodologies should play a greater role in this field, while qualitative methodologies have traditionally been preferred in foresight studies (e.g. Delphi methodologies). Bibliometric analysis of publications and patents and analysis of submitted project proposals 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;
- At the same time, the qualitative methodologies and in particular the panels of experts should be redesigned
  - with the involvement of experts from many disciplines (while more homogenous experts in terms of knowledge are traditionally involved)
  - and with representatives from different stakeholders (while no or few stakeholders are normally involved);
- Given the early phase of nanotechnology development, the time horizon that has to be considered in the foresight analysis should range from mid-term to long-term;
- Similarly, given the diffusion of nanotechnology, a worldwide perspective is necessary in terms of both knowledge production and exploitation.

Although these points are not completely new in literature and in ongoing or already completed studies, their combination for the analysis of future impacts of nanotechnology presents unique challenges and further studies will be useful to understand which methodologies would be the best to foresee and guide the paradigm change.

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