foresight

Russian S & T Foresight 2030: case of nanotechnologies and new materials

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Russian S&T Foresight 2030: case of nanotechnologies and new materials

Abstract

Purpose

The goal of this paper is to apply foresight methodology to the area of nanotechnologies and new materials within the framework of Russian S&T Foresight 2030 aimed at revelation major trends, most promising products and technologies.

Design/methodology/approach

To achieve this goal best international practice was analyzed that provided a solid basis for Russian S&T Foresight 2030 (section 'Nanotechnology and new materials'). The study used a wide range of advanced Foresight methods adapted to Russian circumstances. During the foresight study we integrated "market pull" and research "technology push" approaches including both traditional methods (priority-setting, roadmaps, global challenges analysis), and relatively new approaches (horizon scanning, weak signals, wild cards, etc.).

Findings

Using the methods of the Foresight we identified trends with the greatest impact on the sphere of nanotechnology and new materials, promising markets, product groups, and potential areas of demand for Russian innovation technologies and developments in this field. We assessed the state-of-the-art of the domestic research in the area of nanotechnologies and new materials to identify "blank spots", as well as parity zone and leadership, which can be the basis for integration into international alliances and positioning of Russia as a center of global technological development in this field.

Originality/value

The results of applying foresight methodology towards revelation of the most prospective S&T areas in the field of nanotechnologies and new materials can be used by a variety of stakeholders including federal and regional authorities, technology platforms and innovation and industrial clusters, leading universities and scientific organizations in formulation their research and strategic agenda. Russian business including both large companies and SMEs can use results of the study in creating their strategic R&D programs and finding appropriate partners.

Keywords

Foresight; nanotechnologies; new materials; advanced materials; convergence; NBIC technologies; composite materials; Russia

Introduction

Development of nanotechnologies and new materials sector represents one of the most promising scientific and technological trends on which depends the growth of key sectors of national economy (OECD, 2014; RAND, 2006; Tegart, 2004; Roco, 2015).

In recent years, nanotechnologies have become much more affordable both from an economic and technical point of view: modelling has become possible, as well as processes and process control on nano-levels (Diallo, Brinker, 2011; GAO, 2014).

The development of this field is stimulated by a growing demand for new materials, caused, on the one hand, by depletion of natural resources and, on the other hand, by active introduction of nanotechnologies into the production of goods with fundamentally new properties. Due to nanosystems and materials created using nanosystems, in the near future there may come to be effective solutions for numerous problems in industries such as energy, health care and food production (European Commission, 2006, 2009; Future markets, 2013b; Horizon 2020, 2016).

According to optimistic assessments, the first noticeable effects, primarily in nanoelectronics, photonics, nanobiotechnology, medical products and equipment, neuroelectronic interfaces, and nanoelectromechanical systems, can be expected as early as within the next five years. The largest breakthroughs of the next decade may include the molecular production of macroscopic objects ("desktop nanofactories") and the emergence of atomic design. The convergence of nano-, info-, bio-, and cognitive technologies may potentially lead to extending the active stage of human life by dint of 3d bioprinting, targeted drug delivery and other solutions (Kim et al, 2014; Roco, 2015).

The above-mentioned areas would potentially largely determine the level of technologies of the future. The greatest expectations are first of all associated with the development of hybrid structures combining organic and non-organic fragments, live tissues and synthetic components capable of giving them new properties; the development of nanocomposites, which would make it possible to make materials of unique strength, elasticity and conductivity – particularly important for achieving progress in alternative power engineering; and mathematical modelling of nanomaterials' properties, which is expected to significantly accelerate creation of new systems with useful properties (Accenture, 2006; Resnik Institute, 2011; Stockman, 2011; Vishnevskiy, Karasev, 2014).

Nanotechnologies can make a significant contribution to solving global problems, help in shaping the responses to such challenges of world development, as the global population growth and the depletion of natural resources as well as improve the quality of life of the citizens. Moreover, the active introduction of new materials and nanotechnology is also a necessary prerequisite for improving the global competitiveness of the country in terms of increasing the pace of scientific and technological progress (UN, 2015; UNDP, 2014; ITU 2014; Molitor, 2000).

Nanomaterials will also play a major role in dealing with economic problems, since they are at the core of advanced sensing and water treatment technologies, separation processes in recycling, and a bunch of “green chemistry” areas. They serve as a basis for the development of numerous drugs, targeted delivery systems for them, and express diagnostics technologies for live organisms. A significant step towards solving the economic problems of food availability will be the development of new drugs based on nanoparticles to increase period of storage, product protection at the stage of production and realization (Hanford et al, 2014; OECD, 2013a, 2013b; WHO, 2013).

In order to reveal what are the most prospective market niches for nanotechnologies and new materials, what kind of innovation products have the breakthrough potential and which technologies should be employed for their elaboration we suggest a special Foresight methodology.

Long-term future studies in the area of nanotechnologies and new materials

The issues of the development and adoption of new kinds of technologies and prospective materials has been inalterably attracting future explorers' attention during the last decades. The sector of nanotechnologies and new materials as evidenced in a variety of Foresight projects has undoubted significance for successful future development (APEC, 2004; ATSE, 2008; Cuhls et al, 1998; Karasev et al, 2011; Loveridge, 1995; NASA, 2010; NISTEP, 2005, 2010c).

The pioneer of the new materials development forecasting is Japan where the large-scale expert research Delphi has held every 5 years since 1971. In general there are 2900 of experts who participated in the preparation of the 9th Science and Technology Foresight Survey till 2040 (NISTEP, 2010a,b,c).

Within the scope of this project experts were suggested to evaluate scientific researches and technologies in the sphere of nanotechnology and advanced materials and reveal forecasted time of technological and social realization. The project allows researchers to define a set of concrete recommendations for policy forming within the sphere of new materials and nanotechnology. The suggested package of measures is the basis of priority definition of Japan science and technology Basic Plan (Vishnevskiy, Karasev, 2010; Vishnevskiy et al, 2016; NISTEP, 2010a,b,c).

One of the first and at the same time the largest scale European study aimed at the development of prospective materials was “Delphi-98” (Cuhls et al., 1998) that started in Germany in 1996. It was based on a list of 1070 topics classified into 12 sections (informatics and connection, services sector, energy and resources, space etc.). The research consisted of two phases with participation of about 7000 specialists — representatives of science, business, non-commercial organizations. 260 experts participated in the first round of the survey on the section “Chemistry and Materials” and 206 experts in the second round.

The German project aimed at meeting a wide range of challenges related to the definition of priority pathways of science and technology development. Its organizers tended to raise the level of public information awareness concerning prospective scientific and technological trends and to help business and the government to form development strategies.

The authors of the German Forecast borrowed a part of topics from Japan Delphi survey. The grouping of research subjects was different too. Area of new materials was represented within the section “Chemistry and Materials”. It included 104 products: high-temperature polymers, composite-biomimetics, lignin as advanced materials for chemical industry etc.

Like in Japan Foresight projects in this project there was undertaken an attempt to model a list of concrete measures indispensable for successful development of advanced technologies and products. Among such measures the most significant are: education quality improvement, international cooperation, enhancement of researches infrastructure etc (Vishnevskiy, Karasev, 2010).

During the XXI century Foresight for nanotechnology and new materials became a widespread phenomenon in Europe and covered different countries and institutions (Lust et al., 2008; DG-R, 2010, Nanofutures, 2012). Some of these projects were related to whole area of nano. One of the most representational examples here was realized by NANOfutures European Technology Integrating and Innovation Platform (ETIP). It was established to foster the use of nanotechnology. To achieve this goal NANOfutures Integrated Research and Innovation Roadmap (2013-2025) was elaborated. During the process of Foresight around 700 participants were involved in these activities. It includes detailed implementation plan focusing more on actions up to 2020, 5 key nodes and 27 examples of lead markets and a set of final nano-enabled products (production chains), cross-cutting actions that overarch the roadmap (societal chains). Experts mark 7 nano-enabled value chains including Lightweight Multifunctional Materials and Sustainable Composites; Nano-Enabled Surfaces for multisectorial applications; Structured Surfaces; Functional Alloys, Ceramics and Intermetallics; Functional Fluids; Integration of Nano; Infrastructure for Multiscale Modelling and Testing (Nanofutures, 2012).

Nowadays nanotechnologies and advanced materials consider as the key-enabling technology (KET) and major driver in building an innovation European Union as a part of the EU Framework Programme for Research and Innovation (Horizon 2020) one of the major aims of that is achieving Leadership in Enabling and Industrial Technologies (Horizon 2020, 2016).

Area of advanced materials and nanotechnology included in the USA research agenda since 2000-2001 when National nanotechnology initiative was started. Within the framework of National nanotechnology initiative the USA develop regularly strategic plan that includes a description of the NNI investment strategy and the program component area. There are four major goals of this initiative:

- Advance a world-class nanotechnology research and development program.
- Foster the transfer of new technologies into products for commercial and public benefit.
- Develop and sustain educational resources, a skilled workforce, and a dynamic infrastructure and toolset to advance nanotechnology.
- Support responsible development of nanotechnology (NSTC, 2014).

Considering this strategic plan a variety of long-term future activities was carried out in the in the sphere of new materials and nanotechnology (e.g. NIST, 2009; DoE, 2010; IAM NSTC, 2012; MPSAC, 2012).

The range of new materials and nanotechnology issues was represented also in Russian Foresight studies. One of the pilot projects touches with new materials and nanotechnology was a long-term forecast of S&T development of Russian Federation prepared on Ministry of Education and Science's request by National Research University “Higher School of Economics” in 2007–2009.

The project was aimed at defining of the most important scientific and technological results that can be achieved till 2025 and identifying key technologies and the most prospective market niches where Russia could occupy firm competitive positions. Within the framework of the project there was accomplished an estimation of eventual economic and social effects connected to the new technologies development. In this project there was suggested a set of recommendations on measures of scientific and technological and innovation policy that encourage a faster growth of the most important technological trends.

The whole section “Industry of nanosystems and materials” was focused on the problems of the new materials development. 319 specialists participated in the first round of the appraisal of this trend, and 145 in the second one.

This study proved significant prospects for polymeric materials, crystalline and nanostructured metal materials, materials for communication systems including materials for fiber optics, filters and membranes based on nanomaterials. As the result a scientific, methodological and organizational base for Foresight researches was created according to the leading foreign practice (Sokolov, 2009).

However the most significant project in this field was realized by National Higher School of Economics for Rusnano. During this study the broad-based Foresight study was conducted and a set of detailed roadmaps for the most prospective areas was created. Foresight study allows revealing the most prospective nanotechnology applications, assess potential markets dynamics and Russian perspectives on the world market. The list of the most prospective markets for nanotechnology in Russia includes aerospace industry, pharmaceuticals and medical devices, transport and the road infrastructure etc. (Vishnevskiy, Karasev, 2013).

Roadmaps reflect the prospective directions of using nanotechnology in sectoral applications (nuclear energy, space industry, aircraft industry, medicine and others) and certain product groups (light-emitting diodes, composite materials, catalysts for oil refining). They allowed to give a comprehensive understanding of nanotechnology development prospects in various fields and to form innovation chains R&D-technology-product-market. Using roadmapping led to estimation of the possibility of innovative development of production, to correlate them with the existing and future needs for products. For instance, roadmap for composite materials includes six layers:

- Main technological trends, necessary R&Ds and alternative directions of development in the field of composites.
- Most prospective products and time of their anticipated market maturity.
- Market prospects of products based on carbon fibers, forecasts of volume, and growth rates of key market segments.
- Alternative technologies, their competiveness and major competitive advantages.
- Forecast of most important consumer and application properties.
- Main barriers and limitations for the carbon fiber industry (Vishnevskiy et al, 2015a).

However, the recent trend in activities connected to new materials and nanotechnologies is the convergence of technologies (OECD, 2014; Roco, 2015). There are 3 major levels of convergence:

- Nanotechnologies
- NBIC – nano-, bio-, info and cognitive technologies (Sia, 2014)

- Beyond NBIC – converging knowledge, technology and society (Roco, 2015)

Thus, the importance of advanced materials and nanotechnology will remain at the high level in the future and can be expanded beyond initial limits. That's why it's necessary to take into account cross-sectoral effects and consider this topic together with other prospective areas' development.

Such comprehensive approach was employed within the Russian S&T Foresight 2030 (table 1).

Table 1. Examples of long-term future initiatives related to nanotechnologies

<Insert Table 1>

Methodology

Russian S&T Foresight 2030 is based on wide range of advanced Foresight tools, based on the best international practice and adapted to Russian particularities. During the Foresight study we integrated normative ("market pull") and research ("technology push") approaches to forecasting. Normative approach is characterized by a problem-oriented (market) nature: first of all the key challenges and windows of opportunities were identified for the selected scientific and technological areas, and then the relevant decisions in terms of "technology packages" or other responses were revealed. Research approach was aimed at identifying promising products and technology breakthroughs that could fundamentally change the existing economic, social and industrial paradigm. Recommendations of the study formed simultaneously from three positions — science, business and government, which allowed not only to identify promising areas of research and development in dialogue with different groups of beneficiaries, but also to understand who and how will be able to benefit from their development.

As prediction tools we used as already become traditional methods (priority-setting, future visioning, global challenges analysis), and relatively new approaches (weak signals, wild cards, etc.) (fig. 1).

Figure 1. Methodology of the study

<Insert Figure 1>

First of all we identified trends with the greatest impact on the sphere of science and technology, and then defined challenges of long-term development of the economy, science and society in global and national contexts generated by the revealed trends. Some of them are marked as wild cards and weak signals due to their probability and potential effect.

The methodology of trend monitoring includes 10+ methods including text mining, clustering, expert polling, in-depth interviews, weak signals etc. and contains 4 stages:

- Scanning and monitoring.
- Data analysis and integration.
- Discussions. Validation. Priority-setting.
- Updated trend database (nowadays it includes about 2 mln scientific articles and 10,000 research fronts).

Based on the identified trends we designated windows of opportunities for Russia. Using combination of qualitative and quantitative methods of foresight we revealed and prioritized promising markets, product groups, and potential areas of demand for Russian innovation technologies and developments (e.g. patent and bibliometric analysis etc. to identify and expert panels to prioritize). It was drawn up a detailed description of the priority thematic areas of science and technology and formulated the priorities for research and development necessary to be done for the appearance of the groups of innovation products and services. We assessed the state-of-the-art of the domestic research in these areas: identified "blank spots", as well as parity zone and leadership, which can be the basis for integration into international alliances and positioning of our country as a center of global technological development. Finally, we formulated recommendations aimed at increasing the use of the results of the study in science, technology and innovation policy, including the formation, adjustment and implementation of state programs of the Russian Federation, including the federal target program of scientific and technological orientation.

More than 100 specialists including business, academia, and government bodies in the area of nanotechnologies and new materials in Russia were participated in the study for this field.

Findings

As evidenced outcomes of Russian S&T Foresight 2030 the development of new materials and nanotechnologies in the medium (5 to 7 years) to long (till 2030) term will be determined by challenges and opportunities conditioned by global trends (fig. 2) among which:

- increasing environmental standards for manufacturing;
- global shortage of energy sources and raw materials for the production of new materials;
- possible negative impacts of nanoproducts on human health and safety;
- spread of new contaminants (including nanoparticles) in the environment (wild card);

- threat of uncontrolled proliferation of nano-enabled products that haven't been adequately tested for their safety for human (wild card).

Figure 2. Challenges and Opportunities for development of New Materials and Nanotechnologies

<Insert Figure 2>

Legend: vertical axis reflects impact of revealed trends on Russia, -2–0 — challenges; 0–2 — opportunities

New higher demands on production linked, on the one hand, to safety and, on the other hand, to protecting the environment are in many ways shaping key vectors in the development of nanotechnologies in the future.

New types of light composite materials which are superior in strength and cost effectiveness over existing ones will take on a critical role. The scope for their application is extremely large: from the aerospace sector to the sports industry and medicine. Moreover, the use of composite materials will contribute to the development of high-speed transport which, in turn, will have a favorable influence on changes in people's lifestyles.

The use of biomimetic materials and medical materials, in particular surgical implants, will raise medical care up to a new level.

Technologies allowing computer modeling of materials and processes show great promise. Using such technologies it will be possible to model nanomaterial growth, aggregation, self-assembly and self-organisation processes, which will make it possible to achieve the desired structure and characteristics using a minimum number of actual experiments.

New opportunities are opening up in relation to the creation of prospective electrical engineering materials, including developing fundamentally new telecommunications properties, elements of environmental and spacing monitoring systems, thermal imaging, nanodiagnostics, robotics, precision weapons, ways to combat terrorism (e.g. sensors that can detect the presence of toxic substances in the air, quantum devices for cybersecurity), etc. Currently the nature and performance of electrical engineering, lighting technology, and device capabilities is undergoing fundamental changes thanks to the introduction of nanotechnologies and functional nanomaterials. The broadening scope for using nanostructures in the next 5-7 years will make it possible to significantly reduce the dimensions of devices (for example, observation and recording methods), reduce their energy consumption, improve cost characteristics and benefit from the advantages of mass production of micro- and nanoelectronic components and systems.

The scope for application of new methods of material diagnosis which make it possible to monitor the status of complex systems exposed to physical and chemical influences will significantly increase. By using nanotechnologies new systems to visualize and study the surface of materials at atomic resolutions will be able to be developed.

The development and use of new materials and nanotechnologies will be a serious driver behind the modernization and development of production methods, infrastructure and the social sphere. In particular, the dissemination of production technologies based on molecular self-assembly could come to be a major breakthrough. A "desktop nanofactory" based on simple hydrocarbon feedstock molecules such as natural gas, propane, or acetylene can produce macroscale quantities of atomically precise diamondoid products such as nanocomputers and medical nanorobots. According to expert assessments, a relatively small molecular-precision device will be able to produce an object with a volume of approximately 1 liter and a mass of roughly 4 kg within about three hours (Nanofactory Collaboration, 2017).

Intelligent and customizable functional and structural materials with high levels of strength, plasticity, lightness, transparency and reflective properties could in future be used in current metals and plastics. With the transition to these materials there will be further increases in the demands placed on the technical properties of products, in particular with respect to resistance to radiation and corrosion, high and low temperatures, and material ageing.

There is expected to be active dissemination of functional coatings and laminated materials which will be used in the engineering industry (parts exposed to friction and high temperatures, etc.), the production of devices for various fields (medicine, metal- and wood-processing), etc.

Experts have outlined the following threats to Russia in this field:

- lack of modern scientific and industrial equipment for designing and producing new materials and nanoproducts;
- barriers for import of technologies and materials;
- shortage of high-quality raw materials for the manufacturing of nanoproducts;
- lack of highly qualified personnel;
- intense competition with foreign manufacturers;
- need for substantial investment in the organisation of mass production to achieve the economy of scale.

In order to manage these risks it is vital to create a system of priorities in the given field and reveal the most prospective innovation products and market niches for them.

The changing face of the economy and society is in many ways linked to the widespread integration of new materials and nanotechnologies into production processes and the services sector. Like in the ICT (Information and communications technology) sector, innovative markets for nanotechnology products and new materials are becoming an integral part of larger industry markets, many of which base a significant proportion of their production on nanotechnologies and new materials.

The experts were in agreement regarding the majority of application areas – future markets for nanotechnologies and new materials. In the short (nearest 2–3 years) and long term (till 2030) the main field of application for these materials is likely to be electronics. Functional nanomaterials will be used in virtually all computer and radio-electronic technology and in the vast majority of home appliances. However, according to expert assessments, if in 2015 the share of electronics on the nanotechnology market in Russia is likely to exceed three quarters, then by 2030 it will fall to one fifth. This will occur on account of the expanding use of new materials in the automotive and aerospace industries, shipbuilding, the food processing industry and housing construction. In the long term, the emergence of markets which would combine large volumes and high growth rates is expected, specifically: mining and processing equipment, pharmaceutical and medical equipment, power engineering (fig. 3).

Figure 3. Innovative Products and Services with a Radical Impact on the Dynamics of World Markets

<Insert Figure 3>

Legend: radar demonstrates innovative products and services with a radical impact for short-, mid- and long-term

Physical value sensors based on nanomaterials could be used in special measuring devices. They comprise two sub-groups of innovative products:

- electromagnetic wave measurement sensors: hard x-ray, ultraviolet, infrared, radio emissions, etc.;
- sensors designed to measure linear and angular displacement (produced using materials made from carbon nanotubes with zero transverse deformation coefficient), acceleration (based on the tunnel effect with sensitive nanoelements), and terahertz radiation using planar nanostructures (based on ultra-thin metal films). This sub-group also includes optical nanosensors for mechanical stress (based on elastic inverted photon crystals), etc.

In the short term we can expect to see the emergence of *nanostructured materials and reagents for water purification processes* (water treatment, raw food processing). With the transition to these technologies, the problems of drinking water supplies and efficient purification of household and industrial sewerage will largely be solved, in particular by using various types of hybrid membranes with embedded nanoparticles (Goh & Ismail, 2015). It is possible to significantly intensify water transport processes using membranes with an asymmetric (gradient) distribution of nanoparticles by restructuring membrane pore and channel structures and reallocating ion concentration profiles in membranes. Such an effect can occur upon implementation of electromembrane technologies, allowing for an increase in the electrocatalytic activity of particles in a water dissociation reaction, and hybrid membranes with embedded nanoparticles with catalytic activity for water dissociation processes and higher speed electrodialysis purification of water in extreme currents. Ion-exchange and membrane materials containing nanoparticles of metals are used for further removal of dissolved oxygen from water, which is extremely important for a number of processes in today's electronics industry.

In the near future (3-5 years) we can expect active development in technology to create *nanostructured bio-compatible materials* for medical use, primarily in two areas:

- developing materials to manufacture implants and substitutes for various tissues (for example, oxide or phosphate bio-coatings are applied to strong and relatively light titanium implants to prevent rejection by living tissues);
- the creation of materials with properties and structures similar to those found in the human body. One example is bone implants with a porous structure based on calcium phosphate. Ideally, medical materials should complement natural fabrics. With the emergence of nanostructured bio-compatible and bioresorbable implants, the structure of the prostheses and implants market, together with the principles and approaches to prosthetics, have changed significantly. The introduction of new technologies will make it possible to increase the active life of humans, reduce population disabilities, and improve people's quality of life.

The use of *drug delivery systems* will radically increase the effectiveness of drug treatments. Highly-porous nanoparticles or nanocapsules could be used as drug carriers. Targeted delivery systems are contributing to cost-effective spending on medicinal substances and reductions in their toxicity, as opposed to significantly level out their side effects.

New types of light and high-strength materials primarily relate to products based on carbon fibers. Their most important characteristics (high elastic and strength qualities, lightness, low friction coefficient, resistance to atmospheric effects and chemical reagents) and special features of their structure make it possible to combine carbon fiber materials with other types of fibers: boric, glass, and aramid. As a result, light and strong products can be created, combining the competitive advantages of two source materials. Such hybrid composites have already found application in the aerospace sector and sporting equipment industry. Other materials which meet the criteria of lightness and high strength can be created on the basis of nanostructured alloys or aluminum, titanium and several other metals.

The most in demand will be the following products:

- high-strength mixtures based on nanostructured polymers;
- polymer composite materials with the addition of small quantities of carbon nanoparticles;
- stronger composite materials based on nanomaterials using wood (Isogai, 2013);
- nanostructured composite materials based on light metals – Al, Ti, Mg – containing nanofibers made from super-high-molecular polyethylene, etc.

A lot of research groups are actively developing technologies relating to nanostructured *materials for chemical sources of electrical current*. Their use will make it possible to increase the specific capacity of electrodes, increasing the capacity of power sources and allowing for their miniaturization and safety. An important parameter is also the increasing operating temperatures of these energy sources. Among the most promising chemical sources of electrical current are the following:

- lithium-ion batteries;
- fuel cells.

Broad prospects for the development of nanotechnologies are offered by *radiating elements based on nano-scale heterostructures*, including lasers and organic light emitting diodes. Organic light emitting diodes, one of the most cost-effective sources of light, are renowned for their unique slim design and high flexibility, offering a broad range of the light spectrum and light stream geometries to which humans are readily accustomed. They can be manufactured in any form, almost at will, and "fit" into working and residential premises of different scales. Lasers have already been widely used in medicine, mechanical engineering, construction and land surveying following the development of the printed circuit board and integrated boards.

They are used to detect various substances (including weapons and explosives), for heating through thermonuclear synthesis and in astronomy.

Heat-resistant nanostructured composite, ceramic and metallic materials have considerable potential for application in numerous fields (in particular the aeronautical industry and electrical energy sector) thanks to their resistance to chemical degradation at high temperatures. Among this line of innovative products, the following are notable:

- carbon-carbon construction materials with maximum operating temperatures of up to 1650°C;
- light high-strength laminated composite metal-intermetallic materials suitable for use in high temperatures and at critical temperature gradients;
- heat-resistant composite coatings hardened with nano-scale silicides making it possible to increase the temperature and operating life of products, as well as their reliability by 1.5 times;
- carbon fiber composites with metallic matrices to produce heat-resistant construction items with a certain nanostructure.

Nanostructured composite materials with special properties (including conductive, magnetism and optical), intended to transfer and transform electrical currents, make up a large group of innovative products. The main applications for this type of materials are being developed to transfer high power currents and to miniaturise devices.

Nanostructured composite materials with special optical properties (including photon crystals) will be particularly in demand by 2030. In the medium term we can expect to see the use of systems with sensory properties, for example, the ability to change the range of intensity of emitted light in conjunction with certain reagents. There may significant improvements in key functional parameters of fibre-optic communications lines providing safely screened multi-channel methods to transfer data – speed and quality of the transfer – by using nanostructured materials, on the one hand, with extremely high levels of immunity to interference and, on the other hand, which are not a source of radiation. The application of photon crystal and micro-structured fibers opens up new opportunities to use fiber-optics in physical value sensors.

Nanostructured anti-friction and adhesive materials will find wide application in various industries. Among the most promising materials and products in this group are:

- separators of high-temperature rotating bearings capable of working without lubrication in aggressive environments;
- inorganic composites containing carbon nanotubes and graphene;
- bearings containing nano-scale modifying additives;
- wear-proof nanostructured composite materials generated using special powdered production methods;
- polymer lubricants containing inert nanoparticles (ZnO, SiO2, TiO2, SiC, carbides and nitrides of tungsten, titanium) to improve mechanical characteristics;
- multi-layer nanocomposite polymer coatings for interior finishing of pipes to reduce the friction coefficient, etc.

Fuel cells and catalysts for innovative energy sources will be able to use the large number of nanotechnological materials used to design various types of energy sources. In particular, these include:

- hybrid nanostructured proton-conducting membranes including nanoparticles which improve their transmission properties, and nano-scale catalysts based on platinum and transition metals (including "core in the shell" type catalysts) used to create fuel cells;
- nano-scale cathode materials with mixed electron-ion conductivity and nanostructured anode materials based on various forms of silicon and carbon, from which lithium-ion batteries are formed (Peng et al, 2014);
- a wide range of nano-scale catalysts to produce innovative and process natural energy sources;
- nano-scale granular membranes based on complex oxides with a perovskite, spinel and fluorite structure, used in processes to partially oxidize methane and associated gases into synthesis gas at low temperatures, or nano-scale catalysts to convert biomass products into synthesis gas (Batra & Li, 2017).

Nano- and microrobotics systems appear to be very promising in terms of their use in medicine, including developing next-generation surgical devices. In this group, promising products include:

- movable elements of nano- and microrobotics systems based on laminated nanocomposite materials;
- integrated equipment based on mechatronic modules to machine complex parts;

- active nanostructures based on magneto-elastic materials and multiferroics with artificially created critical states, designed for micro-electromechanical systems;
- mechatronic modules used for spatial positioning of nanosystems and nanotechnological equipment based on incremental micromotors, roller drives and microprocessor control systems.

An important breakthrough in the electronics industry will be the development of *electronic elements based on graphene, fullerene, carbon nanotubes and quantum dots*. The electronic devices developed on the basis of these, with very small dimensions and weights, will have very high functional parameters. It is anticipated that after development of the frequency range up to several terahertz and significantly increasing the performance of computer systems, fundamentally new communications devices could be created with unprecedented broad-band channels. This will open up a new niche for high-speed data transfer networks with small ranges and will make it possible to completely abandon the use of cables when connecting audio, television and video devices and home cinema equipment when transferring multi-threaded video at high resolution. Graphene photodiodes, used as photo receivers in the terahertz range, could be mounted in compact security systems (to detect arms, drugs, explosives, etc.).

New opportunities to create neuromorphic computer systems with a revolutionary new architecture will be opened up by *memristor-based electronics*. This drastically increases their performance when solving problems which have been poorly programmed on classic computers, and significantly reduces their energy consumption. In the field of "smart" electronics, it may be possible to make controlled changes to the electrical resistance of functional materials with long-term storage of the specified status, which will make it possible to use these structures as equivalents to synapses when setting up the hardware for neural networks and building neuromorphic computer systems.

As for the distant future (beyond 2025) it is worth mentioning *molecular self-assembly*. Products in this group can find the greatest use. Thus, self-assembling microchips can become especially cost-effective, productive and energy-efficient. There is serious potential for medical applications, in particular to develop diagnosis methods and targeted drug delivery systems.

Implications for Russia

During the analysis leading Russian and foreign research centers which are actively carrying out work in this field have been identified for these products. The most notable successes in the field of new materials are seen among organizations from the USA, EU (primarily, Germany, the Netherlands, the United Kingdom), Japan and South Korea. With regards to nanosensors, it is hard to single out any leaders as research is being carried out by both small firms and major research centers. Drug delivery systems and nanomaterials for medical diagnostics are being developed by the vast majority of major pharmaceutical companies, but not exclusively – among this group the Dutch company Philips is also active. In Russia there are competitive teams in the Russian Academy of Sciences research institutes, as well as in state scientific centers and leading higher education institutions.

Russia's opportunity to play a role in the trends outlined above and even to occupy a leading position in certain fields is in many ways determined by the level of scientific and technological groundwork, in respect of which four main promising areas have been identified (fig. 4).

Figure 4. Structure of priority directions

<Insert Figure 4>

Legend (assessment of the level of Russian research):

 — “possibility for alliances”— the existence of a limited number of competitive teams carrying out research at a high level and able to cooperate with global leaders “on an equal footing”

 — “S&T backlog (“groundwork”)” — the existence of basic knowledge, skills, infrastructure which could be used to boost development of the corresponding areas of research

Unlike the majority of Russian S&T priority directions, the level of Russian research in nanotechnologies and new materials has been appraised relatively highly by experts, in particular in fields such as the development of nano-scale catalysts for deep processing of raw materials and the creation of nanostructured membrane materials. However, there are some "blank spots" where the results of the research carried out in the country have been recognized as poor. “Blank spots” represent those areas of research in which Russia tends to lag behind the world level. These include, among others, the development of construction materials for the energy sector.

Conclusions and recommendations of the work can be used by various stakeholders in the field of new materials and nanotechnology: federal authorities, government corporations and development institutions, state-owned and private companies, technological platforms and clusters, universities and scientific organizations (fig. 5).

Figure 5. Stakeholders of the study and directions of using

<Insert Figure 5>

The results can be used by federal executive bodies when implementing public programs connected to new materials and nanotechnologies (e.g. “Development of aircraft engineering”, “Development of shipbuilding industry”) of the Russian Federation, as well as when adjusting them. Russian state corporations (Rusnano and Rostec) can use results of this study to coordinate their strategic directions, major state-owned companies can reveal promising technological directions to update their corporate innovation development programs.

There are a number of technology platforms and innovation clusters in the field of new materials (Advanced polymeric and composite materials and technologies platform; Materials and technologies of metallurgy platform; Titanium cluster; New materials, laser and radiation technologies cluster etc.) that also can employed outcomes.

Leading Russian universities and scientific organizations are able to update their research agenda in order to prepare students with modern skills satisfied major priority directions. Russian business including both large companies and small and medium-sized enterprises can employ results of the study in elaborating their strategic R&D programs and finding appropriate partners.

Areas for further research

Research limitations are caused by the scope of the S&T Foresight 2030. The study covers 7 areas with a participation of more than 2000 experts and 200 organizations. Thus, for each field, including nanotechnologies and new materials, we identified major trends, markets, products and prospective S&T areas. The next step is an elaboration action plans for them how to improve the competitiveness of sector. We plan to realize it during the next cycle of Russian S&T Foresight 2040 within the roadmapping framework to suggest innovation routes for the subject area.

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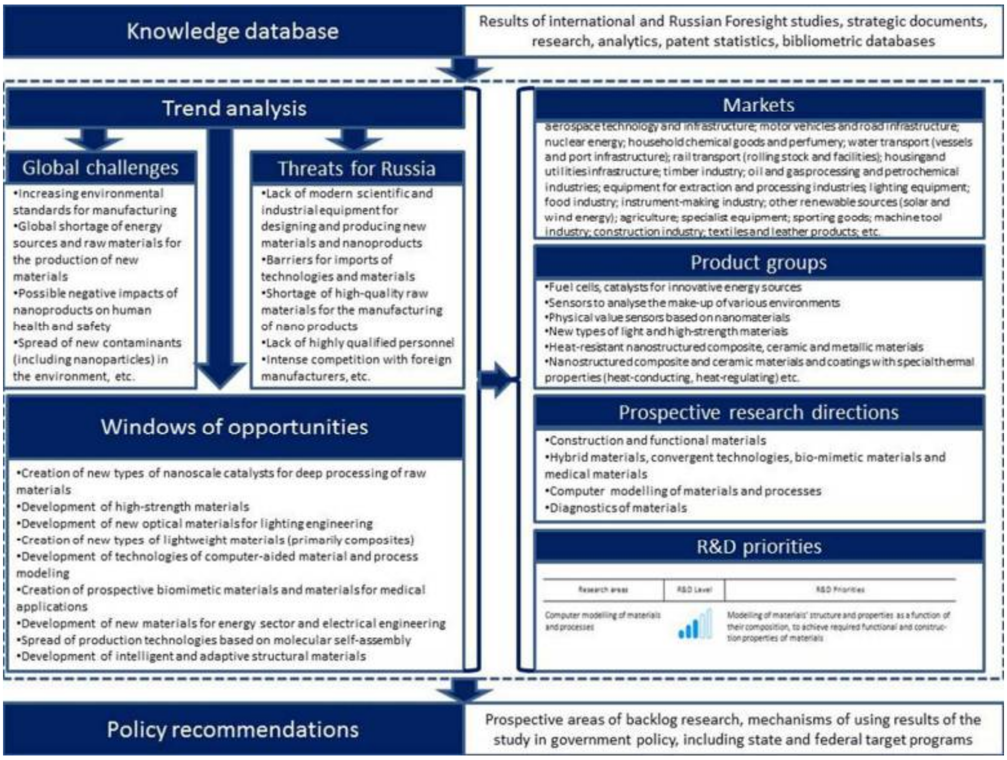


Figure 1

254x190mm (96 x 96 DPI)

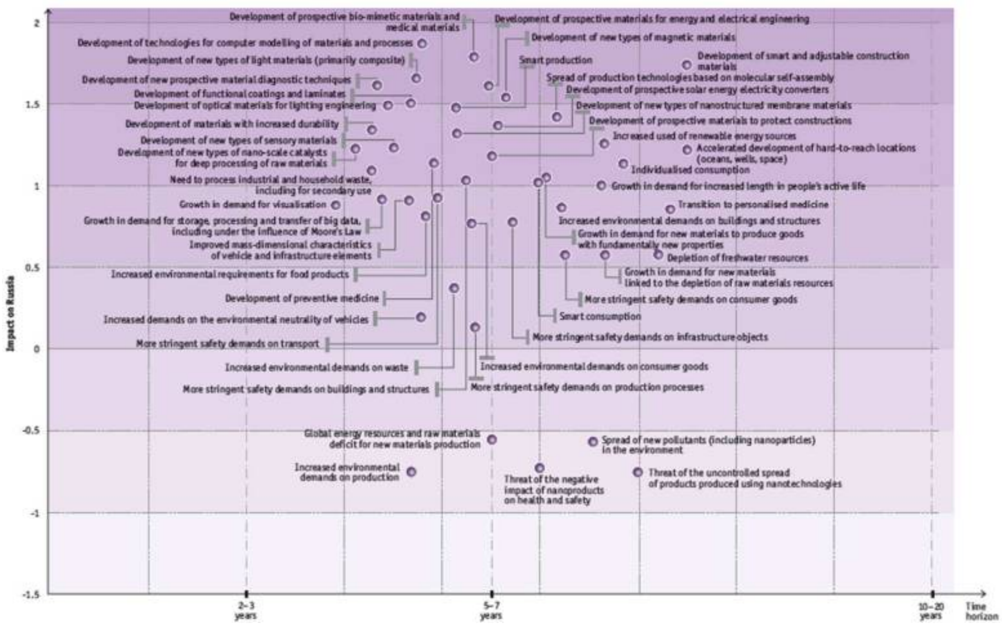
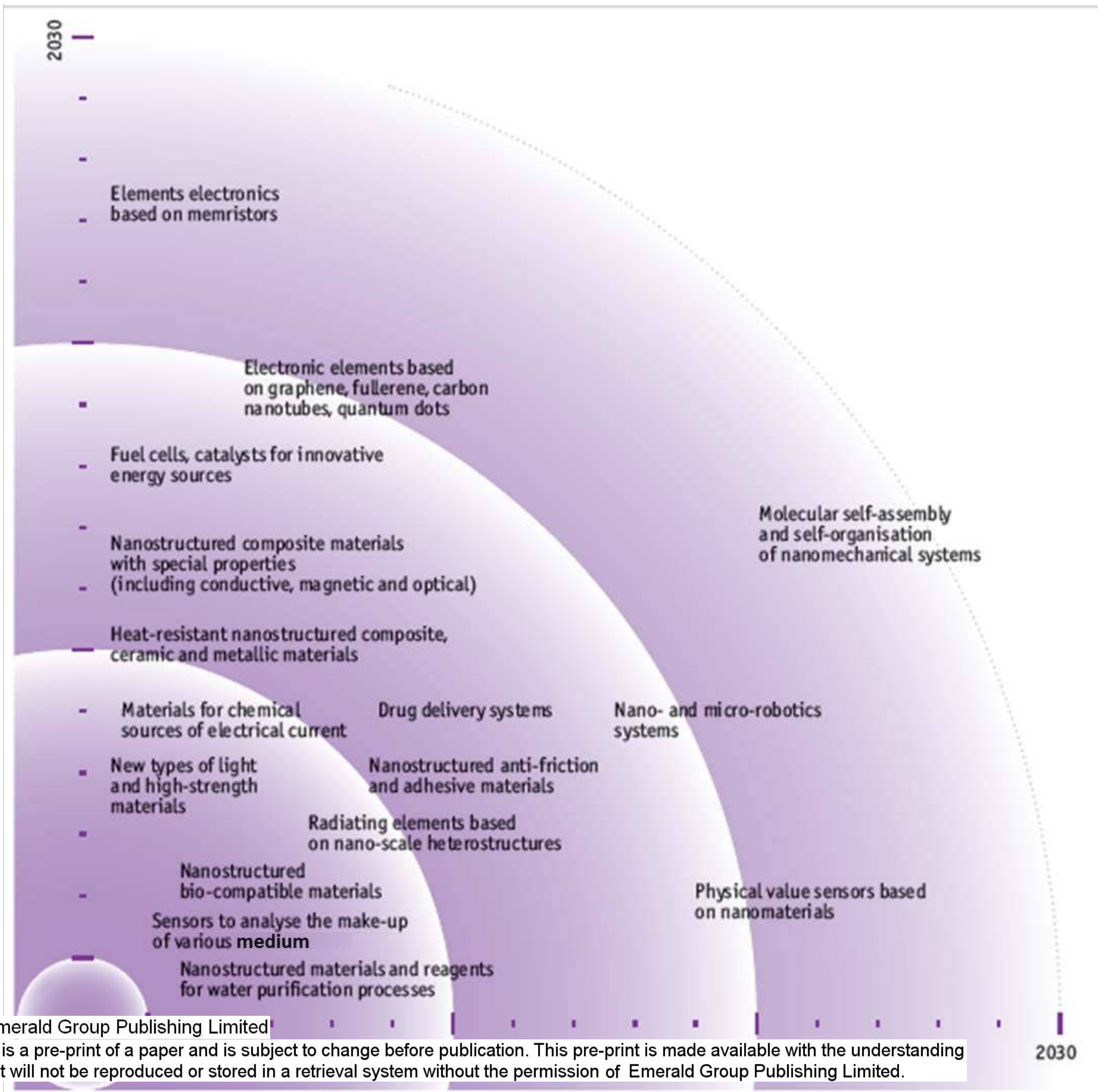
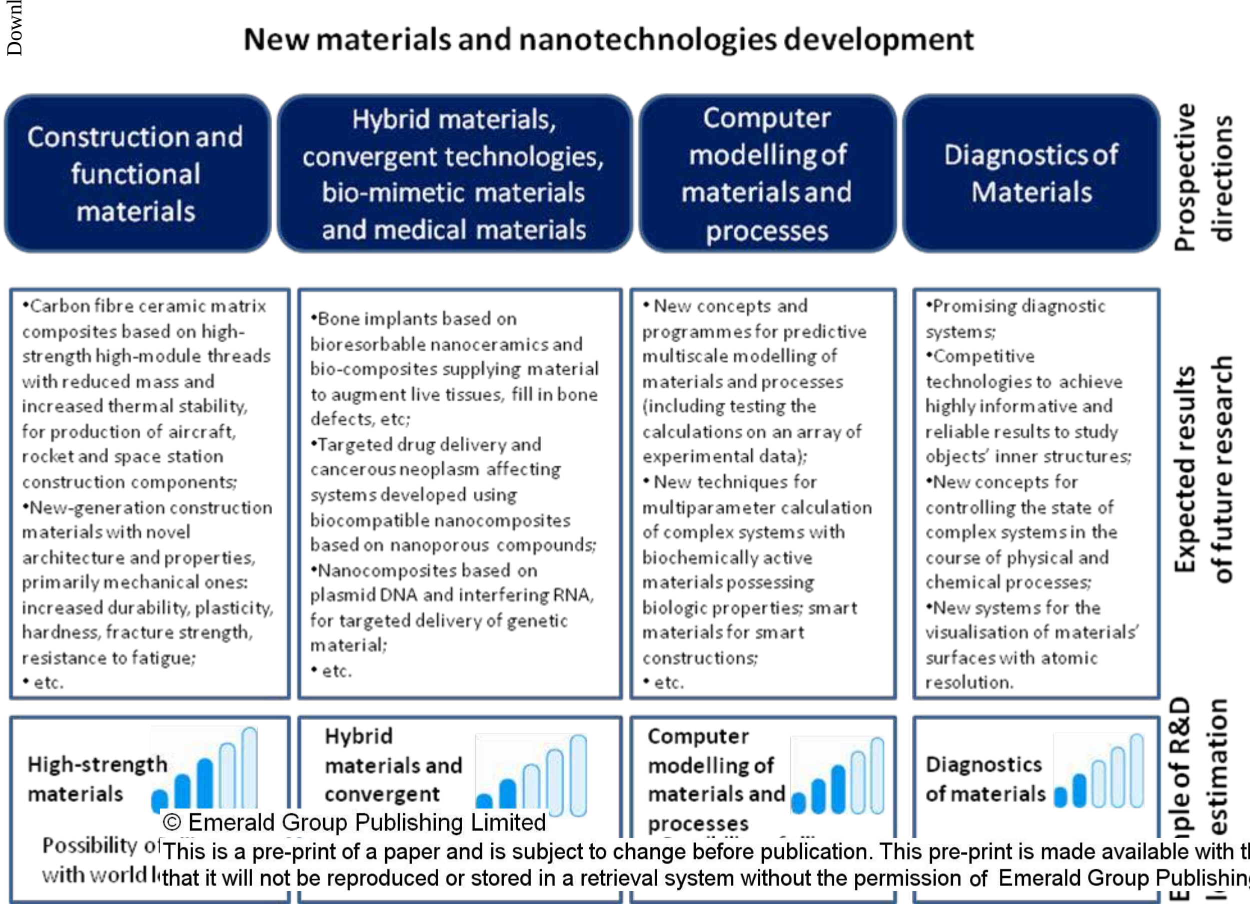


Figure 2


2030
Elements electronics
based on memristors
Electronic elements based
on graphene, fullerene, carbon
nanotubes, quantum dots
Fuel cells, catalysts for innovative
energy sources
Molecular self-assembly
and self-organisation
of nanomechanical systems
Nanostructured composite materials
with special properties
(including conductive, magnetic and optical)
Heat-resistant nanostructured composite,
ceramic and metallic materials
Materials for chemical
sources of electrical current
Drug delivery systems
Nano- and micro-robotics
systems
New types of light
and high-strength
materials
Nanostructured anti-friction
and adhesive materials
Radiating elements based
on nano-scale heterostructures
Nanostructured
bio-compatible materials
Physical value sensors based
on nanomaterials
Sensors to analyse the make-up
of various medium
Nanostructured materials and reagents
for water purification processes
2030


New materials and nanotechnologies development
Construction and functional materials
Hybrid materials, convergent technologies, bio-mimetic materials and medical materials
Computer modelling of materials and processes
Diagnostics of Materials
Prospective directions
•Carbon fibre ceramic matrix composites based on high-strength high-module threads with reduced mass and increased thermal stability, for production of aircraft, rocket and space station construction components;
•New-generation construction materials with novel architecture and properties, primarily mechanical ones: increased durability, plasticity, hardness, fracture strength, resistance to fatigue;
• etc.
•Bone implants based on bioresorbable nanoceramics and bio-composites supplying material to augment live tissues, fill in bone defects, etc;
•Targeted drug delivery and cancerous neoplasm affecting systems developed using biocompatible nanocomposites based on nanoporous compounds;
•Nanocomposites based on plasmid DNA and interfering RNA, for targeted delivery of genetic material;
• etc.
• New concepts and programmes for predictive multiscale modelling of materials and processes (including testing the calculations on an array of experimental data);
• New techniques for multiparameter calculation of complex systems with biochemically active materials possessing biologic properties; smart materials for smart constructions;
• etc.
•Promising diagnostic systems;
•Competitive technologies to achieve highly informative and reliable results to study objects' inner structures;
•New concepts for controlling the state of complex systems in the course of physical and chemical processes;
•New systems for the visualisation of materials' surfaces with atomic resolution.
Expected results of future research
High-strength materials
Hybrid materials and convergent
Computer modelling of materials and processes
Diagnostics of materials
Possibility of
with world l

Stakeholders of the study and directions of using

Federal authorities		Government corporations / development institutions		State-owned companies	
Ministries of economic development, education and science, industry and trade etc.	Development and realization of sectoral strategic planning documents, government and federal target programs	Russian corporation of nanotechnologies, Russian technologies state corporation	Coordination of priority directions, creation and stimulation of demand	Gazprom, Aeroflot, Rosneft, etc.	Realization and actualization of corporate innovation development programs

Technological platforms and clusters		Universities and scientific organizations		Private companies	
Advanced polymeric and composite materials and technologies platform, New materials, laser and radiatic technologie cluster, etc.	Realization and actualization of strategic documents	National research center “Kurchatov Institute”, National University of Science and	Specification of priority directions, actualization of educational and research agenda	Large private corporations, small and medium-sized enterprises	Development and implementation of research and production programs and projects, finding technology

Table 1. Examples of long-term future initiatives related to nanotechnologies

Country	Examples of initiatives	Major methods	Outcomes
Japan	9th Science and Technology Foresight Survey	Delphi, scenarios, panels	Integration into S&T basic Plan, set of concrete recommendations for policy forming, prospective S&T areas and topics
Germany	Delphi-98	Delphi	Priority pathways of S&T development, policy recommendations
Europe	NANOfutures, Horizon 2020	Expert panels, scenarios, roadmap	Prospective markets and nano-enabled products, detailed implementation plan focusing more on actions up to 2020
USA	National nanotechnology initiative	Roadmap	Investment strategy
Russia	S&T Foresight 2025, S&T Foresight 2030, Foresight for Rusnano	Broad base of quantitative and qualitative methods, including Delphi, roadmap, expert panels	Global trends and its impact on Russia, list of the most prospective markets, products and areas for R&D, wild cards