Nanomaterials and nanotechnology: prospects for technological re-equipment in the power engineering industry

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Abstract. The authors substantiate the potential of nanotechnology in the technology modernization of the power engineering industry (PEI) enterprises aimed at achieving production efficiency growth. The key factors encouraging the PEI companies to undertake technological re-equipment (stable and rapid nanotechnology market growth, expanding nanomaterials application and reducing costs along with the increase in the global energy consumption) are revealed. The authors state that the opportunities for the widespread use of the new nanotechnologies and nanomaterials in the PEI are directly related to the formation of regulatory and technical support for the life cycle of nanotechnology products. Within that framework, formation of the global and Russian system of standardization and certification in nanotechnology field is exercised. The factors restraining the process of the PEI companies’ technology modernization (the lack of funds, delay of standardization, metrology and certification in relation to the pace of nanotechnology development, insufficient companies’ interest) are disclosed. Prospective algorithm of technological re-equipment of the PEI companies is suggested.

1. Nanomaterials and nanotechnology for the power engineering industry projects: market trends

Nanotechnology continues to have a broad impact on nearly all sectors of the global economy [1], primarily electronics, energy generation and energy storage, computers, telecommunication and information technologies, medicine and health, chemical and biological technologies, etc. Power engineering industry (PEI) companies that are engaged in production of machinery and equipment for the generation, transmission and storage of electrical energy, and oil, gas and mining equipment can stimulate an additional and differentiated demand for nanotechnology and nanotechnology products.

The demand for nanotechnology in all industries in the world is evidenced by the ever-growing volume of investment made by the private investors (corporations and funds) and at the expense of the state budgets. The United States remains the global leader in the volume of nanotechnology government investment by the end of 2018. The cumulative National Nanotechnology Initiative (NNI) investment since fiscal year 2001, including the 2018 request, now exceeds USD 25 bln. In addition, more than USD 1.1 bln have been invested cumulatively since 2004 in supporting nanotechnology-based small businesses through the profiled programs of the authorized federal agencies. The
President’s 2019 Budget includes nearly USD 1.4 bln for the NNI realization to provide a continued investment in fundamental research, early-stage applied research, and technology transfer [2].

The result of the active development of applied research in the field of nanotechnology is the continuing increase in the number of patents: in 2017, the number of international patents on nanoobjects, nanotechnologies and nanoproducts has reached 189,000 that is 31,000 more than in 2016. The largest national players in this market are China (the number of nanotechnology patents is over 88,000), the USA (86,000 patents), Japan (25,000 patents) and South Korea (22,000 patents). Over the past 20 years, more than 620,000 patent applications in the field of nanotechnology have been filed [3, p. 34]. Ranking of leading countries by the number of nanotechnology patents registered in the European Patent Office (EPO) and in the United States Patent and Trademark Office (USPTO) at the beginning of 2019 can be seen from table 1 below [4].

Table 1. EPO and USPTO top nanotechnology patent activity by countries, 2018

| Country       | Nanotechnology patents in EPO | Rank | Country       | Nanotechnology patents in USPTO | Rank |
|---------------|--------------------------------|------|---------------|----------------------------------|------|
| USA           | 856                            | 1    | USA           | 4,343                           | 1    |
| Germany       | 355                            | 2    | South Korea   | 887                             | 2    |
| Japan         | 318                            | 3    | Japan         | 640                             | 3    |
| France        | 288                            | 4    | China         | 520                             | 4    |
| South Korea   | 251                            | 5    | Taiwan        | 427                             | 5    |
| United Kingdom| 114                            | 6    | Germany       | 309                             | 6    |
| Switzerland   | 103                            | 7    | France        | 236                             | 7    |
| China         | 90                             | 8    | Saudi Arabia  | 162                             | 8    |
| World         | 2,908                          |      | World         | 8,493                           |      |

Mostly used nanomaterials in the global PEI market are graphene, fullerenes and other carbon nanostructures, materials with the nanolayer and cluster-fractal structures, metal oxide nanoparticles, nanocomposite coatings and some others. Table 2 [5] provides characteristics of contemporary global patent activity on selected nanomaterials (including mentioned above) that are widely applied by the companies in the power engineering industry.

Table 2. USPTO nanotechnology patent activity on the selected PEI nanomaterials, as of 2018/07/01

| Selected nanomaterials for the PEI needs | Nanotechnology patents in USPTO | Nanotechnology published patents applications in USPTO |
|-----------------------------------------|---------------------------------|-------------------------------------------------------|
|                                         | Quantity | Rank | Quantity | Rank |
| Nanotubes                               | 1,306     | 2    | 1,541     | 3    |
| Graphene                                | 1,099     | 3    | 1,594     | 2    |
| Nanocomposite                           | 516       | 5    | 692       | 6    |
| Quantum dot                             | 505       | 6    | 763       | 5    |
| Nanoporous materials                    | 254       | 11   | 330       | 9    |
| Fullerene                               | 188       | 12   | 213       | 13   |
The large-scale opportunities of production application of nanotechnology determine the prospects for its market share growth. According to the new Industry ARC research report [6], the global nanotechnology market size was between USD 45 bln to USD 50 bln as of 2018, and the market demand will grow at a compound annual growth rate (CAGR) of 13% during the forecast period of 2019 to 2025. The Research and Markets's Global Nanotechnology Market & Forecast to 2024 Report [1] states that global nanotechnology market is expected to exceed USD 125 bln by 2024. By component, the nanomaterials captured highest share of the global nanotechnology market with nanoparticles’ 85%-share of the global nanomaterials market. The nanotools accounted for second highest share of the global nanotechnology market, and nanodevices amounted for the least share of the market. The top three applications of nanotechnology are electronics, energy and biomedical. Together, they account for over 70% share of the global nanotechnology market.

2. Nanotechnology standardization potential for the power engineering industry development

Since the strategic goal of nanomaterials’ application in the power engineering industry is providing efficiency growth [7] for producers and consumers of the industry products, the promising areas of using nanomaterials in the production processes cover:

– sustainable energy production, involving renewable energy sources (solar energy, and wind, tides and biomass power in particular);
– changing energy from one form to another;
– building machinery, equipment and tools for oil and gas exploration and production;
– reducing unnecessary energy consumption with provision of considerable energy savings, eliminating energy losses while energy transmission and storage;
– reducing carbon dioxide emissions at the fossil-fired gas and steam power plants;
– implementation of the integrated ongoing monitoring of the large-scale energy grids.

However, the opportunities for the widespread use of the new nanotechnologies and nanomaterials in the engineering for the needs of the energy sector are directly related to the formation of regulatory and technical support for the life cycle of nanotechnology products. It involves all stages from development of a new idea to mass production and market launch based on achieving consistency with the requirements of national and international systems of metrology, standardization and certification in the field of nanotechnology and obtaining all necessary permits, including environmental ones.

Developing standards and improving the system of confirming the safety of new materials based on metrological support of nanoindustry products create the necessary institutional foundation for the introduction of innovative nanotechnologies and nanomaterials into mass production in the PEI. Institutional support of the emerging national segments of the global system of standardization and certification in nanotechnology field is reflected at figure 1 and figure 2 [8, 9].

Production application of the certified products, produced by nanoindustry enterprises with the certified management systems, leads to increased competitiveness of PEI companies’ machines, equipment, and tools in domestic and international markets.

The problems of standardization and certification in Russian nanoindustry have been the focus of attention of the Federal Agency on Technical Regulating and Metrology (Rosstandard), the JSC RUSNANO and the Fund for Infrastructure and Educational Programs (FIEP). The RUSNANO official data demonstrate a much more optimistic picture of the current state of standardization and certification in the nanoindustry of the Russian Federation in comparison with the StatNano information (figure 1). Between 2011 and 2017 in Russia, the number of nanotechnology manufacturing types with a developed minimum required regulatory and technical support for entering and safe circulating manufactured products in the market has increased 6.7 times and reached 133 units [10].
Under the FIEP’s aegis, 370 national standards (the "green" ones among them) for innovative nanotechnology products, including 218 with the FIEP funding, have been developed, approved by the Rosstandard and included in the Register of the developed national standards in nanoindustry [11, 12]. The trends in the mandatory and voluntary certification in the nanoindustry of the Russian Federation can be seen in the chart below (figure 3) [12].
Figure 3. Certification trends in the field of nanotechnology in the Russian Federation (units).

The autonomous non-profit organization “Certification centre of products and management systems in the field of nanoindustry” (ANO “Nanocertifica”) has contributed significantly to the establishment of a nanoindustry certification system in the Russian Federation. “Nanocertifica” system’s certificates confirm the compliance of the functional properties and actual advantages of nanotechnology products as compared with analogues, compliance with the requirements of ISO 9001 management systems of the enterprises that manufacture, service or apply nanotechnology products.

At the end of 2018, because of these certification procedures 334 samples of nanoindustry products have been included in the Register of products certified in the “Nanocertifica” system; and 13 companies – in the Register of enterprises that have got “Nanocertifica” certificates for their management systems [9]. Based on the procedures of the “Nanocertifica” system at the beginning of 2019, 80 Russian companies and 138 types of products were entitled to use the Mark “Russian nanotechnology products” (the growth of indicators is 3.3 and 3.7 times, respectively, in comparison with 2014, when the mark has been established).

However, a study of the dynamics of the certification process in nanoindustry of the Russian Federation and abroad indicates insufficient initiative of producers in voluntarily undergoing both mandatory and voluntary certification procedures that does not meet production needs of consumers of the nanotechnology products from the PEI worldwide.

3. Technological re-equipment in the power engineering industry: algorithm, nanotechnology contribution

PEI companies’ technological re-equipment would appropriately be undertaken according to a specific algorithm of proceeding (figure 4), which involves the following main steps:

– expert assessment of the global strategic directions of science, technology and innovation development, identification of the technological breakthroughs that can have an impact on the economy and society in the medium and long run, and selection of the most preferred development option from the available alternatives [13];
Figure 4. Flowchart depicting prospective algorithm of the PEI companies’ technological re-equipment.
– forecasting strategic development of the PEI enterprise that plans implementation of technological re-equipment in the framework of current technological megatrends [14];
– building up an objective tree as the basis of the corporate program of technological re-equipment; building up a resource pool tree to further substantiating the choice of measures to provide the optimal movement along the initially chosen trajectory of innovative development of a PEI company;
– undergoing technological audit, formation of a technology balance sheet or inventory control of existing technologies and other company’s intellectual property;
– monitoring national and world technology market conjuncture; formation of a list of technologies, the most promising in terms of achieving the strategic goals of corporate technological re-equipment;
– justification of the option of technological re-equipment in order to provide the new or fundamentally new types of activities and to master production of the new products; or to expand production of the already developed products, to maintain or increase the PEI company’s market share;
– selection of a new technology from the available nanotechnologies;
– choosing a method of obtaining new technology (development of a technology by independent means or by engaging in the R & D collaborations [15]; purchasing a technology on the market; entry into the patent pool [16]; or some others) determined by the resources available;
– development of a mechanism for financing activities related to implementation of the technological re-equipment program with identifying necessary volumes, sources and channels of funds to achieve the objectives of the PEI enterprise modernization;
– justification and implementation of the relevant organizational innovations;
– introduction of a technology in a timely manner, in a specific unit or division of the PEI enterprise by the designated performers;
– clarification and specification of tasks in the course of program implementation, taking into account factors affecting the characteristics of the technological re-equipment process; combination of measures of adjustment and prolongation of the program.

The results of numerous recent studies exhibit tremendous nanotechnology and nanomaterials potential for technology modernization of the PEI companies aimed at strengthening their market position.

The case of graphene and quantum dots is the example. New battery technologies, for instance, are directly depend on the properties of the objects gained from graphene application, according to the Nanowerk (website https://www.nanowerk.com/). Researchers from Chalmers University of Technology (Sweden) develop lithium sulphur batteries with a theoretical energy density 5 times more to compare with lithium ion batteries. This breakthrough effect is expected due to the use of a porous sponge, made of reduced graphene oxide, functioning as a freestanding electrode in the battery cell and providing better utilization of sulphur (which is cheap, available, and environmentally safe). The next example is new graphene coating, being developed by researchers from College of Engineering of the University of Illinois, Chicago (USA), which could help prevent lithium battery fires because of batteries overheating or cycling rapidly. One example more is modified white graphene, which has been functionalized as a dielectric by the scientists from Tomsk Polytechnic University (Russia), Germany, and the United States. This new material is regarded as very promising for producing environmentally friendly hydrogen fuel in the energy sector. Applying quantum dots in the production activity of the power engineering industry companies is expected to induce solar cell efficiency growth over 60% in the long-term period.

In conclusion, stable and rapid nanotechnology market growth, expanding nanomaterials application and reducing costs along with the increase in the global energy consumption are the key factors encouraging the PEI companies to undertake technology modernization aimed at achieving production efficiency growth.

However, factors restraining technological re-equipment in the power engineering industry include the following: the lack of funds, delay of standardization, metrology and certification processes in
relation to the pace of nanotechnology development, insufficient companies’ interest against the background of a decline in manufacturing machinery and equipment for the energy sector in certain countries, including the USA [17].

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