Engineered nanomaterials for energy sector: market trends, modern applications and future prospects

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Abstract. The article reveals key trends of the development of the global market for engineered nanomaterials and focuses attention on the energy related market segment based on the studies and generalization of recent analytical reports and research publications in this field. The authors substantiate rapid market growth of the energy related nanomaterials taking into account available proving their unique electrical, thermal, mechanical, optical and catalytic properties, and increasing patent activity in the field under consideration. These factors significantly expand the application prospects of energy related nanomaterials in generation, conversion, storage, saving and transmission of energy in the conventional and renewable energy systems. Within that framework, modern and future applications and growth prospects of mostly used nanomaterials in the global energy market (graphene, fullerenes involving carbon nanotubes, and other carbon nanostructures, materials with the nanolayer structures, metal oxide nanoparticles, and some others) and most recent nanomaterials in the market (aerographene / graphene aerogel, 3D and 4D-printed aerogels) are characterized.

1. Global market for engineered nanomaterials: development trends and energy related segment

Engineered nanomaterials – the nanomaterials that are conceived, designed, and intentionally produced by humans for specific applications [1] have a broad potential application in energy sector and a wide range of other sectors of the global economy. Engineered nanomaterials’ extremely small size and high surface area to mass ratio allow for using quantum effects to control their physical and chemical properties [2]. Among the most common engineered nanomaterials are nanoscale metal oxides (in particular, titanium dioxide, and iron and aluminum oxides), nanoscale polymers, and polymeric nanocomposite materials. Emerging engineered nanomaterials include quantum dots, nanoshells, nanocages, and nanobranches [2] along with the most recent nanomaterials such as aerographene / graphene aerogel, 3D and 4D-printed aerogels [3; 4] etc.

The large-scale opportunities of production application of nanotechnology and nanomaterials determine the prospects for their market growth. In the latest research Global Nanotechnology Market Outlook 2024, the RNCOS analysts expect the global nanotechnology market to grow at compound annual growth rate (CAGR) of nearly 17% during the forecasted period [5]. While BCC analysts optimistically predict global market for nanotechnology growth at a CAGR of 19.4% by 2023 in their 2019 Nanotechnology and Advanced Materials Research Review [6].
The global nanotechnology market is expected to reach more than USD 91.8 billion by 2028, growing at a CAGR of 15.80%, in terms of revenue, between 2020 and 2028. [7]. According to the optimistic estimates in the Research and Markets’s Global Nanotechnology Market & Forecast to 2024 Report [8], the global nanotechnology market will exceed USD 125 billion as late as 2024.

Nanomaterials amount for the highest share of the global nanotechnology market by component. In terms of volume, the global nanomaterials market is expected to reach 2314.81 kilotons by 2028, growing at a CAGR of 16.10 % during the forecast period [7].

The global nanomaterials market’s value reached USD 7.3 billion in 2016 [9]. In case of continuation of the tremendous rise scenario witnessed in 2017-2019, the revenue in this market (including in particular chemicals and polymers, metal oxide, and metals) is expected to reach USD 16.8 billion by 2022, the end of the Zion Market Research’s forecast period. The Grand View Research analysts’ estimate the global nanomaterials market size in 2019 at the USD 8.5 billion mark and expect the market growth at a CAGR of 13.1% from 2020 to 2027 [10]. The Global Industry Analysts’ experts have expressed a balanced approach in evaluating the prospects of the world nanomaterials market growth driven by a compounded growth of 15.2%. They projected the growth of the market up to USD 15.9 billion by 2025 in their 2020 report “Nanomaterials – Global Market Trajectory & Analytics” [11]. The growth trends in the nanomaterials market are generalized in the chart below (Figure 1) [12; 9; 10].

![Figure 1](image_url)  
**Figure 1.** Global value of nanomaterials market, optimistic and pessimistic view (USD billion).

The factors of nanomaterials market growth include by region: rising product application in North America; expanding mass production and price reduction of nanomaterials in Europe; ease of entry for new players due to the government financial support and increasing demand, along with rising environmental consciousness in Asia-Pacific. Partnerships, mergers & acquisitions, business expansion, and product & application strategies provide leading positions of the key players in the market [13].

Since applying engineered nanomaterials bring new opportunities for improving performance of energy generation, transmission and storage systems in conventional, renewable and nuclear energy systems, energy sector is among the top three application areas of nanotechnology, with the 2nd position after electronics and following by biomedical. These three applications, taken together, account for over 70% share of the global nanotechnology market [8].

The Grand View Research analysts project significantly increasing demand for nanomaterials in the energy and power sector and its stable growth at a CAGR of 13.4% over the forecast period of 2020-2027[10], owing to the growing attention of researchers and producers to nanoparticles use in creating batteries, fuel cells, and photovoltaic film coatings for solar cells. It is therefore not surprising that nanoparticles amount for the 85%-share of the global nanomaterials market [8]. Graphene nanoparticles are expected to exhibit fastest growth over the forecast period 2020-2027, expanding at a CAGR of 14.6%, due to extensive applications in energy, environmental, and biomedical science [10].
The global energy-related market for nanotechnologies is projected to grow from USD 5.7 billion in 2018 to USD 10.0 billion by 2023 at a CAGR of 12.0% for the period concerned [6].

Production application of the latest engineered nanomaterials in the nuclear energy systems improves the efficiency and safety of nuclear power generation and use. Nuclear nanotechnology deals with the use of engineered nanomaterials for future nuclear energy applications such as nuclear fuel extraction and fabrication, fission product capturing, creating robust reactor materials, radiation sensing and monitoring, and radioactive waste separation and spent nuclear fuel reprocessing [14]. Expanding use of nanomaterials in different areas of the nuclear energy sector is a direct result of the rapid development of applied research in the nuclear nanotechnology field accompanied by increased number of patents. Stable growth of patent activity of organizations of the State Atomic Energy Corporation Rosatom (ROSATOM), the largest producer of electricity in the Russian Federation that ensures over 19% of the country’s energy needs, during 2015-2017 can be seen from Table 1 [15].

Table 1. Patent activity of the ROSATOM organizations, 2015-2018 (units)

| Indicator | 2015 | 2016 | 2017 | 2018 |
|-----------|------|------|------|------|
| Number of granted patents for inventions, utility models, industrial designs, certificates on computer programs and databases, number of institutionalized know-how | 1,141 | 1,090 | 1,286 | 500 |
| Number of pending applications for state registration of protectable results of intellectual activity | 853 | 1,038 | 1,073 | 296 |
| Number of international patent application filings and granted patents | 101 | 321 | 443 | 417 |

However, Figure 2 demonstrates clear downward trend in the patent activity related to the nuclear engineering in the United States Patent and Trademark Office (USPTO) during 2015-2018 [16].

Figure 2. The number of the USPTO patents for the nuclear engineering, 2008-2018 (units).

Whereas the strategic goal of nanomaterials’ application in the energy industries is reducing production cost and providing efficiency and performance safety growth for producers, the most
promising areas of using nanomaterials in the production processes that therefore generate the growth of demand in the market under consideration in the next few years are as follows [17]:

– Reducing unnecessary energy consumption due to the provision of considerable energy savings, and eliminating energy losses in the energy transmission and storage processes.
– Increased usage of engineered nanomaterials in manufacturing electrical and electronic appliances, fuel and solar cells (designing and constructing lithium ion batteries, supercapacitors and photovoltaic film coatings) for energy generation and storage [9].
– Sustainable energy production, involving renewable energy sources (solar energy, wind and tides power); changing energy from one form to another.
– Wastewater treatment through the removal of a wide range of heavy metals from wastewaters with the use of nanoadsorbents.
– Enlarged use of nanosensors serving the instruments for monitoring physical and chemical properties of the regions of large energy generation and conversion systems’ allocation based on detecting and controlling their endogenous and exogenous environmental functioning effects.

2. Energy related nanomaterials: market trends and key applications

The specific unique electrical, thermal, mechanical, optical and catalytic properties and functions of nanomaterials significantly expand the scale of their energy related applications, in particular energy generation, conversion, storage, saving and transmission. Inorganic nanomaterials’ excellent electrical and thermal conductivity, large surface area and chemical stability, make them highly competitive in energy applications [18]. The thermoelectric, piezoelectric, triboelectric, photovoltaic, catalytic and electrochromic nanomaterials have made major contributions to various energy applications.

Mostly used nanomaterials in the global energy market are graphene, fullerenes (carbon nanotubes, nanorods) and other carbon nanostructures, materials with the nanolayer and cluster-fractal structures, metal oxide nanoparticles, nanocomposite coatings and some others.

The global graphene market size was estimated at USD 78.7 million in 2019 and is expected to grow at a CAGR of 38.7% between 2020 and 2027 [10]. The Allied Market Research experts has evaluated the market at the USD 91.3 million mark in 2019, and project its growth up to USD 1,369.1 million by the end of the forecast period, with a CAGR of 40.2% during 2020-2027 [19].

Increasing demand for renewable, lightweight, and flexible materials plays the key role in driving the product’s modern and future market relevance, along with significant factors involving the superior product characteristics, e.g. high electrical and thermal conductivity, accompanied with high electron mobility and high permeability that actually have given the name of the “wonder material” to the product. The abovementioned factors in their totality expand the application field of graphene including energy storage, semiconductors, and sensors and accelerate future market growth.

By region, North America accounts for the highest share of the global graphene market in 2019 owing to the U.S. leading role as one of the key exporters of graphene-based products, and is expected to maintain a leadership position over the forecast period. Numerous collaborations among manufacturers and research institutions aimed at focusing on the R & D activities and developing industrial applications of graphene-based products support the U.S. leadership in the market. However, Asia-Pacific graphene market would face the fastest growth between 2020 and 2027.

Improving energy storage and generation by using graphene and layered materials in supercapacitors and batteries, perovskite solar cells and hydrogen fuel cells continues to be a focus of attention of the EU Graphene Flagship research and application projects [20], which cover designing and constructing lithium ion batteries using graphene-silicon anodes that would exceed available analogues.

Some of the key players operating in the global graphene market are ACS Material LLC, Bluestone Global Tech, CVD Equipment Corporation, Graphene Nanochem PLC, Graphenea S.A., G6 Materials, Haydale Limited, Nanotek Instruments Inc., Vorbrck Materials, and XG Sciences [19]. As a whole, according to the StatNano information, 468 renewable energy related nanotechnology products are being produced by 153 companies in 28 countries of the world thus far [21].
Despite the toxic nature and the risks arising in graphene production and application processes that restrain the global graphene market development, significant growth is projected in graphene application in energy storage segment of the market by 2027.

According to the report “Global Fullerene Market – Analysis by Type, by Application, by Region, by Country (2018 Edition): Forecast to 2023”, the market is expected to exhibit a stable growth with a projected CAGR of 8.44% during the forecast period [22]. The carbon nanotubes segment of the market is projected to expand its scale due to the unique properties of the product such as high tensile strength, high electrical and heat conductivity, and relative chemical inactivity. These are the factors that increase opportunities for fullerenes applications in renewable energy sector, in manufacturing batteries and capacitors during the period up to 2023 [23].

Carbon nanotubes accounted for the largest market share of 26.9% in 2019. The product is widely used in lithium ion batteries and supercapacitor electrodes production. Their large surface area and thermal conductivity allow their usage as an electrode catalyst support in the proton exchange membrane (PEM) fuel cells [10]. The U.S. lead the market due to large application of nanotubes (energy storage, etc.) [13]. Carbon nanotubes market will exhibit CAGR of 18.2% during the period 2020-2025 [24].

Metal oxides nanomaterials accounted for nearly 76% of revenue in 2019. Metal oxides are widely applied in fabrication of sensors, piezoelectric devices, microelectronic circuits, fuel cells, anticorrosion coatings, and are useful as catalysts [9].

The revenue of the global iron oxide nanoparticles industry has been valued at USD 928.72 million in 2017 and is expected to reach USD 1769.41 million by the end of 2023, growing at a CAGR of 11.05% between 2018 and 2023. The production is estimated at 2828.05 ton in 2017 and is forecasted to reach 5454.18 ton by the end of 2023, growing at a CAGR of 11.21% between 2018 and 2023 [25].

The global titanium dioxide market size was valued at USD 15.76 billion in 2018 and is expected to witness a CAGR of 8.7% from 2019 to 2025. Accelerating demand for lightweight materials to enhance safety and fuel-efficiency will drive the future market growth [26]. Titanium dioxide nanoparticles segment of the market is estimated to reach USD 4.1 billion by 2027 [10].

Titanium dioxide based ruthenium nanocatalyst has much potential for the photo-production of hydrogen from methanol and water mixtures under UV and visible illumination conditions [27]. Such product may have future application in industrial production of hydrogen fuel with the use of sunlight.

Aluminum oxide nanoparticles are used in a diverse range of applications owing to their exceptional structural and physicochemical properties, including superior resistance to mechanical stress, chemicals, and wear. Key factors of their demand growth involve, firstly, low cost of preparation, and secondly, ease of availability and handling [10].

Uranium and plutonium oxide has good prospects for application in manufacturing uranium-plutonium mixed oxide fuel – a high-density nuclear fuel with nano-sized additives.

Enhancing environmental safety necessitates the development of nanotechnology to avoid and decrease the risks that accompany the nuclear energy generation. Water treatment after radioactive dust dispersal during uranium mining and enrichment is one of the prominent applications.

Modern studies acknowledge successful use of engineered magnetite nanoparticles in removal of heavy metals from wastewaters [28]. Increasing demand for the product in bio-medical, electronics, wastewater treatment, and energy applications is expected to drive the global magnetite nanoparticles market. The size of the market was estimated at USD 43.9 million in 2018 and is expected to grow at a CAGR of 10.3% over the period 2019-2025 [29].

The use of nanocellulose as an adsorbent may also assist solving the water treatment problem. Nanocrystalline cellulose (that is a naturally occurring material isolated from wood and various plants) is highly demanded in paper processing (27.7% of the global nanocrystalline cellulose market), composites manufacturing and biomedical applications. Steadily growing demand drives the market, which is expected to grow at a CAGR of 31.0% between 2018-2026 [30]. Nanocellulose-based nanocomposites application also covers fuel cells and solar cells construction, while nanocellulose paper gives the opportunity of manufacturing thin, flexible and high performance lithium-ion batteries.
Nanosensors are sensing devices with at least one of their sensing dimensions being up to 100 nm. In the field of nanotechnology, nanosensors are instrumental for detecting physical and chemical changes, monitoring biomolecules and biochemical changes in cells, and measuring toxic and polluting materials to reduce and eliminate negative environmental impacts of industrial processes. Nanosensors, in view of this, are useful in the development of highly sensitive and informative systems for managing the quality of the nuclear systems assembly and operation, diagnostics and monitoring physical and chemical properties of the regions under irradiated nuclear fuel storage and recycling to ensure guaranteed environmental safety of atomic energy use and comfortable living environment.

The nanostructured materials used in manufacturing of nanosensors involve nanoscale wires, carbon nanotubes, thin films, metal and metal oxides nanoparticles etc. [31]. The nanosensors market size is expected to grow by USD 3.21 billion during 2018-2022 [32].

3. New energy related nanomaterials for future application in the energy systems

Most recent nanomaterials in the global energy related nanomaterials market are aerographene/graphene aerogel, 3D and 4D-printed aerogels [3 ; 4 ; 35] that have significant nanotechnology potential for production application. The case of graphene aerogel is the example. Graphene aerogels are promising materials for energy systems due to their porous hierarchical structure that provides rapid electron/ion transfer, superior chemical and physical stability, and good cycle performance. Areas of the product application include supercapacitors, lithium-ion batteries, hydrogen and thermal energy storage, fuel cells and solar cells [33].

Energy storage sector determines to a large extent the opportunities of the aerographene/graphene aerogel market. The global aerographene/graphene aerogel market is expected to grow from USD 51.0 million in 2018 to USD 621.0 million in 2024 at a CAGR of 50.29% [3]. The nanocatalyst segment is the fastest-growing application segment in the global aerographene market, and it is projected to grow at a CAGR of 60.9% from USD 5.2 million in 2018 to USD 106.9 million in 2024. The fastest-growing segment of the market, however, is the automotive segment, which will grow at a CAGR of 75.0% to reach USD 82.0 million by 2024.

By region, Asia-Pacific accounted for the largest share (52.2%) of the market for aerographene/graphene aerogel in 2018, and is expected to grow at a CAGR of 46.3% to reach USD 261.6 million by 2024 due to consistently pursuing energy conservation and efficiency governmental policies aimed at achieving energy self-sufficiency. The European energy storage and conversion market is considered to be one of the most innovative and advanced markets owing to the leading positions of Germany and the United Kingdom in developing energy storage and conversion nanotechnology. Latin America, the Middle East, and Africa are projected to experience the most impressive growth of the market [3]. The growth prospects for Latin American countries (Brazil, for example) are directly related to the accelerating industrialization processes. However, the devastating consequences of the COVID-19 pandemic may significantly hamper Brazil economy modernization and cause the decrease in demand for graphene aerogel in the region.

A new type of graphene aerogel – 3D and 4D-printed aerogel [34] can be applied in sensors and nanoelectronics. The product is very promising for improving energy storage and conversion, separations, and catalysis. The ability to withstand multiple compression and keep its properties during repeated compressions and tensions distinguishes the printed graphene aerogel from the products obtained in a traditional way. One of the practical applications of the new graphene aerogel can be flexible electric batteries, where the large internal surface of the material will serve as an electrode, while the printed structure will provide the required flexibility.

Among key players on the emerging global aerographene/graphene aerogel market are such companies as Aerogel Technologies LLC, American Elements, Aspen Aerogel Inc., BASF SE, Cabot Corp., Graphene 3D Lab Inc., Reade International Corp. and some others [35].

The result of the active development of applied research in the field of nanotechnology is the continuing increase in the number of patents for energy related nanomaterials, particularly engineered
ones. Table 2 provides characteristics of contemporary global patent activity on selected nanomaterials that are applied by the companies in the energy industries worldwide [21].

Table 2. USPTO nanotechnology patents and patent applications on selected energy related nanomaterials

| Selected nanomaterials for energy application | Total number of patents by May 2019 | Granted nanotechnology patents | Published nanotechnology patents applications |
|---------------------------------------------|------------------------------------|-------------------------------|-----------------------------------------------|
|                                             |                                    | Quantity in 2018 | Rank on 2019/05/01 | Quantity in 2018 | Rank on 2019/05/01 |
| Nanoparticles                               | 50,456                             | 1,937            | 1                  | 2,893            | 1                  |
| Graphene                                    | 15,265                             | 1,144            | 3                  | 1,605            | 3                  |
| Nanowire                                    | 13,302                             | 638              | 4                  | 777              | 5                  |
| Nanocomposite                               | 13,860                             | 507              | 6                  | 636              | 7                  |
| Nanocrystalline materials                   | 9,422                              | 296              | 8                  | 397              | 8                  |
| Aerogel                                     | 4,160                              | 154              | 12                 | 260              | 11                 |
| Fullerene                                   | 5,513                              | 148              | 13                 | 215              | 14                 |
| Nanorod                                     | 3,415                              | 100              | 17                 | 173              | 16                 |
| Nanolayer                                   | 500                                | 39               | 24                 | 71               | 22                 |
| Nanocluster                                 | 1,207                              | 31               | 26                 | 37               | 26                 |
| Nanocoating                                 | 296                                | 14               | 28                 | 31               | 28                 |

However, factors restraining the development of the energy related nanomaterials market growth are worthy of note. The most common factors are concerns about the toxic nature of selected nanomaterials and risks arising in their production and application processes, the lag between the need for standardization, metrology and certification and the rate of the nanotechnology development. The most recent factors include the decline in the companies’ interest and investment activities against the background of the negative COVID-19 pandemic impact on business and society. Nonetheless, rapid nanotechnology market growth, expanding energy related nanomaterials application, increasing activities to keep down costs in the conventional and renewable energy systems that perform energy generation, conversion, storage, saving and transmission, along with the increase in the global energy consumption are the key factors driving energy related nanomaterials future market growth.

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