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The role of nanotechnology in revolutionizing energy sector

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Abstract— **The need for modernization of the existing energy sector is driven by globally increasing energy demand, rising carbon emissions, global warming, and climate change. The world tends towards the sustainable and more environmentally friendly energy sector that will meet future energy demands by reducing the usage of raw and non-renewable materials and resources and decreasing energy consumption and pollution. Nanotechnology, as one of the key technologies of the 21st Century, holds the potential to revolutionize the entire energy sector, contributing to the development of more efficient and sustainable energy systems. The implementation of nanotechnology in the energy sector is in the various stages of research, development, and deployment. Nanotechnology's solutions and approaches can help create innovative ways to produce, change, distribute, store and consume energy. This paper attempts to summarize some of the current nanotechnology applications in energy sector, emphasizing the associated benefits as well as risks and concerns. Present nanotechnology-based solution and approaches used in the energy sector confirms nanotechnology's potential to revolutionize the entire energy sector. Alongside the growing use of nanomaterials and nanoproducts, uncertainties on the nanotechnology potentially harmful influence on the environment, health, and safety rise as well, representing a main concern related to nanotechnology applications. In addition to the technological feasibility of the nanotechnology implementation in the energy sector, a wide range of other conditions, such as political, economical and social, influence the rate of implementation and acceptance of nanotechnological innovations in the energy sector.**

Keywords-nanotechnology; energy; sustainability;

I. Introduction

The worldwide energy consumption significantly increases with population growth and industrial development. The global energy demand grows for all forms of energy and it is expected that will rise about 50% until 2030 (Fig. 1) [1, 2]. Approximately 80% of current energy demands are covered by fossil fuels. Coal, oil, and gas are dominant energy sources, but they are non-renewable and one day they will be exhausted. In addition, fossil fuels utilization influences harmfully to both the environment and public health [3-6]. A finite supply of fossil fuels and the health and environmental consequences of their utilization imply the need for the more extensive use of renewable energy sources.

Renewable energy sources like sun, wind, water, tides, geothermy or biomass have a lower climate footprint compared to fossil fuels and if properly managed they can pose minimal health risks [6].

Alongside the increased utilization of renewable energy sources, the satisfaction of ever-increasing global energy demand and solving climate problems at the same time involve the overall optimization of the energy value chain (development, conversion, distribution, storage and utilization of energy) [1]. Energy sustainability is, according to the World Energy Council categorized into three components – energy security, energy equity, and environmental sustainability [7]. With the advanced technologies employed in the energy sector, it becomes sustainable than ever before.

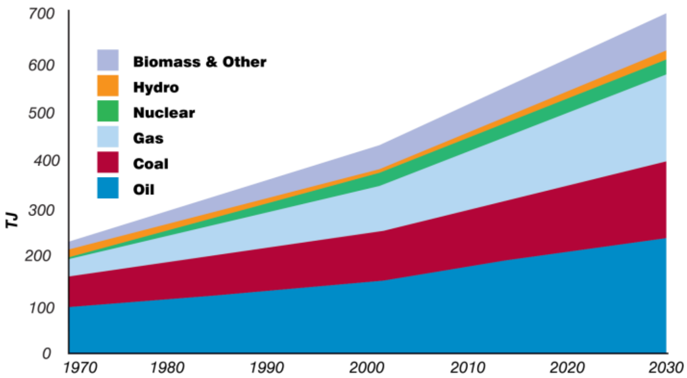


Figure 1. World primary energy demand (TJ) [2]

Among modern and powerful technologies with the potential to revolutionize the energy sector, nanotechnology stands out particularly due to its multidisciplinary nature.

Nanotechnology encompasses engineering, physics, chemistry, biology, and many other disciplines, hence enabling fabrication, characterization, and the manipulation of functional and intelligent nanometer-sized structures with the novel and unique properties. As such, nanotechnology becomes the leading technology of the 21st Century and opens myriad possibilities to revolutionize a wide range of application domains like: environmental, agriculture, medical, space, electronics, computers, transportation, energy, etc. [8].

The application of nanotechnology in the energy sector has been recognized as the most promising and important one [9]. Mass generation of energy via nanotechnology has appeared as a potential approach to sustainability and clean energy. Nanoenergy field became popular after 2000s [10]. As a technology that promises to contribute to a sustainable energy supply chain and global climate protection, nanotechnology possible applications in an energy sector range from energy production, energy conversion, energy distribution, and energy storage to energy utilization at the consumer side.

This paper represents the attempt to summarize as much as possible the role of nanotechnology in the energy sector, emphasizing all the associated benefits and risks. Thus, it is structured as follows. Section II gives a brief overview of nanotechnology. The benefits of nanotechnology utilization in the energy sector are presented in Section III, while Section IV is devoted to the potential risks and challenges. Lastly, Section V contains concluding remarks.

II. A BRIEF OVERVIEW OF NANOTECHNOLOGY

Nanotechnology has the great ability to fabricate, characterize, and manipulate structures at the nanometer scale, resulting in nanodimensional materials with extraordinary sensitivity and accuracy [11]. Physical, chemical, electrical, mechanical and biological properties of nano-scale materials are completely different from the properties of larger-size bulk materials composed of the same substance [8, 12-14].

Nanosized structures' built up approaches are generally classified into top-down and bottom-up methods, using physical, chemical, and green/biological methods (Fig.2) [8].

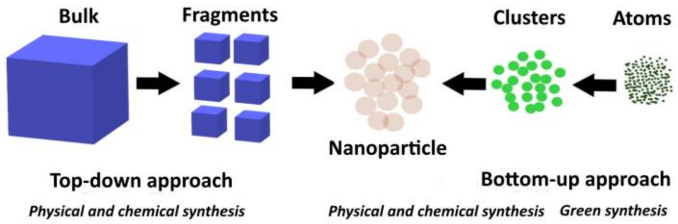


Figure 2. Nanoparticle's synthesis approaches [8]

Nanostructures are generally classified based on their dimensionality, morphology, composition, uniformity, and agglomeration (Fig. 3) [8].

Nanomaterials are materials that have at least one of their dimensions in the nanometric range and therefore they can be classified into 0D, 1D, 2D, and 3D nanomaterials. Nanomaterials can be metals, ceramics, polymers or composites, while wires, tubes, rods, horns, shells, pores and so on, are geometric configurations in which nanomaterials may occur [14].

Nanotechnology development is continuous and until now encompasses four stages [15, 16]:

1. Passive nanostructures (materials designed to perform one task),
2. Active nanostructures (development of highly efficient sensors, actuators, and drug delivery devices that perform multiple tasks),
3. Nanosystems (composed of numerous interacting components), and
4. Molecular nanosystems.

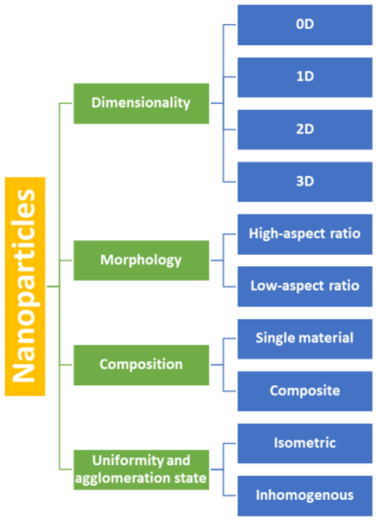


Figure 3. Nanoparticles' classification [8]

Nanotechnology's rapid and spectacular development and production of useful materials and devices lead to its application in a wide range of fields ranging from science to engineering, with a promise to make remarkable improvements in each of them and hence influencing our lifestyle in numerous manners (Fig. 4).

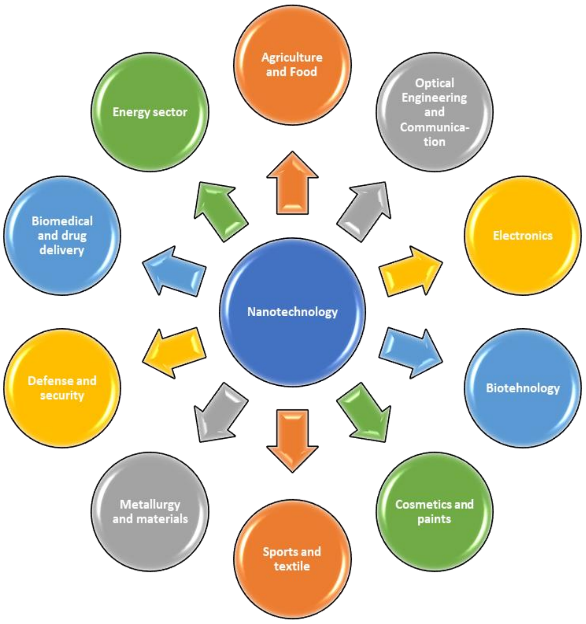


Figure 4. Nanotechnology application domains [8]

It is expected that nanotechnology development after 2020 will be tightly connected with other emerging and converging technologies. Radically modernized materials, devices, communications, and computing imply that very soon there will be no domain untouched by nanotechnology.

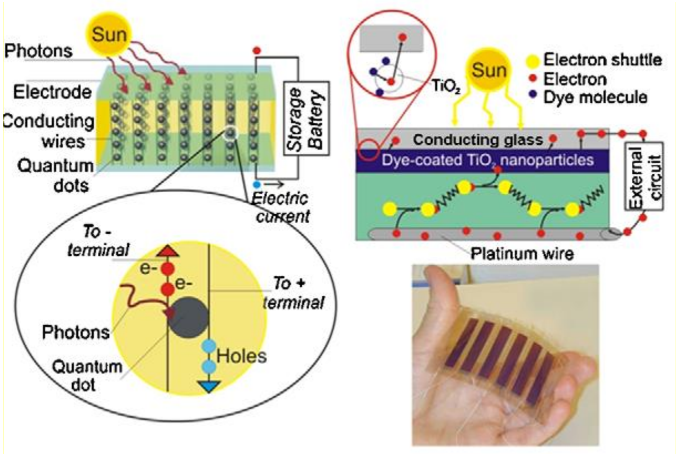
III. NANOTECHNOLOGY UTILIZATION IN THE ENERGY SECTOR

The energy sector is one of the major areas where nanotechnology can bring immense improvements. Nanotechnology applications in the energy sector are possible throughout the entire energy value chain: production, conversion, distribution, storage, and utilization, promising to meet future energy needs. Nanotechnology potential in many fields of the energy sectors consists in more sustainable energy supply, increased energy efficiency in generation and consumption, accompanied with the lower costs and reduced pollution.

A. *Energy production*

Development of conventional energy sources (fossil fuels, nuclear energy) and renewable energy sources (sun, wind, water, biomass, geothermal) can be significantly improved thanks to nanotechnology that enables novel technological solutions and optimized production technologies. Some of the promising nanotechnology utilization in the production of energy include [1, 11, 14]:

- Nano-optimized solar cells made of nanocrystalline silicon and other inorganic or organic nanoscale materials (i.e. flexible polymer-based photovoltaics, thin-layer solar cells, dye-sensitized solar cells (Fig. 5)), antireflective nano-coatings and higher solar transmittance nano-coatings on collector glazing. The efficiency of commercially available solar cells is rarely above 20%. It is expected that nanotechnology advancements will improve the efficiency to be up to 40-50% in the near future.



a) quantum-based solar cell b) dye-sensitized solar cell

Figure 5. Nanostructured solar cells [17]

- Nanotechnology-based improvements in the maintenance, operation, and efficiency of windmills (i.e. nano-composites that enable lighter and stronger rotor blades, nano-coatings for corrosion protection, nano lubricant for improved wear resistance, non-scratch surfaces, and self-cleaning surfaces)
- Wear and nano-coatings for corrosion protection in hydro power systems and fossil fuel systems,
- Nano-coatings and nano-composites for wear resistant drilling equipment in geothermal, oil and gas systems,
- Nanomaterials use for extraction of hydrogen from water,
- Nanomaterials use and nano-optimized cultivation of bio-resources in case of harvesting energy from biomass,
- Nano-composites for radiation shielding and protection in nuclear systems.

B. *Energy conversion*

Nanotechnology can improve significantly the efficiency of energy conversion. Nanomaterials can be used as advanced catalysts (nanoparticulate catalysts, nanoporous catalysts, nanocrystalline catalysts, supramolecular catalysts) for the conversion of primary energy sources into electricity, heat and kinetic energy. Some of the examples of nanotechnology use in energy conversion are [1, 18]:

- Nano-coatings for heat and corrosion protection of gas turbine blades
- Nano-catalysts and new processes for more efficient hydrogen generation (i.e. nano-platinum used as a catalyst for hydrogen production for utilization in fuel cells),
- Nano-optimized electrodes, membranes, and catalysts used for the manufacture of compact fuel cells with enhanced durability for applications in automobiles/mobile electronics and buildings,
- Nanostructured compounds for efficient thermoelectrical power generation,
- Nano-optimized membranes for making coal fired power stations more environmentally friendly,
- Wear and corrosion protection of combustion engine components,
- Nano-composites for superconducting components in electro motors.

C. *Energy distribution*

Power distribution grids of the future will be established on the higher inclusion of renewable energy sources, and require dynamic load, error management, controlled energy supply, reduced energy losses, and flexible price mechanisms. Nanotechnology holds immense potential in the realization of this vision. Nanotechnology applications examples in energy distributions are [1]:

- Nanosensors for intelligent and flexible smart grid monitoring and management,

- Nanofillers for electrical isolation systems and soft magnetic nano-materials for efficient current transformation in high-voltage transmission,
- Optimized nanosized high-temperature super conductors for loss-less power transmission,
- Carbon nanotube conductors are intrinsically different from any existing metallic conductors [19]. They have the potential to enable the way for significant advancements in the performance of existing wiring systems, as well as completely new applications, such as super lightweight electrical machines [20] and high-performance coaxial cables [21].
- Wireless energy transport (laser or microwaves) using nano-optimized components,
- Nano-optimized heat exchangers and conductors for efficient heat in- and outflow

D. Energy storage

As well as for the energy conversion, the energy storage device can also be significantly enhanced by the application of nanotechnology. Nanotechnology has the potential to make energy storage safer, cheaper and more sustainable. The benefits nanotechnology brings to devices for electrical energy storage are: increased efficiency, electrical energy release and electrode materials stabilization against swelling induced damage from ion uptake [11, 22].

Significant advancements in storing energy affected by nanotechnology are present in forms of [1, 17, 18]:

- nanostructured batteries with higher efficiency, energy, power density and safety (i.e. lithium-ion batteries with the enhanced capacity and safety),
- double-layer nanostructured supercapacitors capable of storing unprecedented amounts of charge (used for storing power generated by solar panels or wind farms),
- nanostructures such as carbon nanotubes, graphite nanofibers and zeolites for hydrogen storage (i.e.,nano-porous hydrogen fuel cells)
- Nano-porous materials for reversible heat storage in buildings,
- Nanoparticles in phase-changing materials in thermal energy storage systems enhance the thermal conductivity.

E. Energy utilization

Nanotechnology holds a huge potential to improve energy efficiency. A variety of approaches for energy savings has been enabled by nanotechnology. These approaches are applicable to all branches of industry and in the private sector such as [1, 14]:

- Lighting – lightning devices and large-scale displays (i.e. LED, OLED), dye solar cells as decorative building' facade elements. According to [23], nanotechnology-based lighting promises to reduce global energy consumption by more than 10%.
- Air Conditioning - Intelligent management of light and heat flux in buildings by electrochromic windows, micro mirror arrays or IR reflectors
- Thermal Insulation - Nanoporous foams and gels (applied by spraying or wrapping) for thermal insulation of buildings, ships, in industrial processes, and even clothing and boots (i.e. nanoporous material which traps air, nanocoatings applied on glass to reflect heat, nanofluids added to a home's commercial water boiler that have potential to make the central heating device 10% more efficient, nanofluids in the heating systems of very large reduce energy consumption and contribute to pollution reduction, etc. [18, 24, 25]).
- Industrial processes – the use of nanotechnology-established processes instead of current energy-intensive processes,
- Strong and lightweight construction – nanocomposites-based lightweight and strong construction materials.
- Transportation - nanotechnology use that enables more efficient batteries, lighter, stronger material and catalysts in fuels (that reduce fuel consumption and harmful exhaust emissions) could contribute to more efficient transportation [24].

F. Benefits of nanotechnology in the energy sector

Based on the aforementioned, the benefits nanotechnology brings in the energy sector are [26]:

- Enhanced energy efficiency - application of nanotechnology through the entire energy value chain reduces energy consumption and increase energy efficiency,
- Environmentally friendly energy sector - nanotechnology has the potential to reduce the influence on the environment throughout the energy value chain, providing cleaner and more efficient energy supplies and uses.
- Low costs – nanotechnology application can scale down the cost of energy production, distribution, and storage,
- Independent power sources – nanotechnology use in the energy sector could help in providing alternative sources of energy to the national grid.
- Ease the transition to renewables – moving from fossil fuels towards renewable energy can be facilitated using nanotechnology as it also eases the generation of electricity directly from solar, wind, geothermal and biomass sources.

There is no doubt that nanotechnology will be the main enabler for a wide scope of technologies that achieve low-cost alternative energy production and efficient energy storage and utilization [22].

IV. Health and Environmental Concerns Related to Nanotechnology

In numerous applications, nanomaterials replace toxic substances or substitute more energy-intensive processes [14]. Despite the fact that nanotechnology brings numerous benefits in a diversity of application domains, the information about its influence on the environment and human health is still largely unidentified. Extremely small size, relatively large surface area-to-volume ratio and unique chemical properties of nanomaterials imply their different interactions with the environment in comparison with their bulk counterparts. As nanomaterials unique set of properties (physical, chemical and mechanical) might produce undesirable effects on the environment and humans, a systematic and quantitative analysis of all possible hazards linked with the nanomaterials through their total life cycle is essential. Life cycle assessment helps in addressing the potentially harmful effects of any nanomaterial or nanoproducts during all the phases in which nanomaterials may be found (from the production to the use and disposal). However, the nanotechnology-related risk' evaluation is not simple to perform due to nanoparticles' unique properties and numerous uncertainties about their transportation, transformation, accumulation, and interaction with other chemical and biological substances [8].

Nanotechnology has an immense potential to revolutionize the energy sector making it sustainable than ever before. Nanomaterials can be present throughout the entire energy value chain. However, the emerging uses of nanotechnology in the energy sector and other application domains increase significantly nanoparticles presence and exposure to them [8]. For instance, in the case of nanobatteries, materials input, energy intensity and toxic substances generated in the life cycle of nanomaterials and nanobatteries may have a huge influence on the environment and human well-being [27]. In new types of energy storage, graphene and carbon nanotubes are the most used nanomaterials. Nanomaterials are also utilized as advanced catalysts. However, their release can occur during the manufacturing process or through improper use and/or disposal harmfully influencing the environment and human health [28]. This raises questions and expresses fear over possible human health and environmental implications caused inadvertently or purposely by some types of nanoparticles.

Environmental conditions (i.e. temperature, humidity, light, wind, etc.) also influence the nanoparticles' impact on the environment, while the presence of the nanoparticles in the human body can be intended or unintended. Nanoparticles enter into the body through the skin, via inhalation or ingestion, and through respiratory and blood circulation systems can get to and accumulate in all other organs, potentially causing a variety of diseases such as neurological, pulmonary, autoimmune, gastrointestinal, etc. As the nanotechnology impact to the environment and exposure and risks to humans are still mostly unknown, these issues currently present an increasingly important area of research [8].

The possible approach to take the best from nanotechnology and minimize its potential negative influence on the environment and human health is moving towards green nanotechnology. Greener nanomaterials and nanoproduction methods are the result of utilizing natural and biodegradable substances, environmentally friendly and inexpensive chemicals and with minimum energy consumption. As such, they promise to have little or no harm to the environment and human health. Even green nanotechnology is in its nascent phase, it holds a huge potential in a diversity of application domains as environment-friendly, cost-effective and sustainable technology. Nanomaterials from green synthesis have numerous applications in the energy sector, but the associated challenges and risks still need further analysis and assessment [29].

V. Conclusion

The most important technological challenge modern society faces nowadays is to meet future world energy demand in a sustainable manner. The sustainable energy sector must satisfy energy demands in terms of quantity and quality and to have a minimal impact on the environment. This implies the need for new means to generate, converse, transport, store, and utilize energy in more efficient ways.

Nanotechnology that enables novel materials with unique properties has an immense impact on the energy sector and plays a huge role in the revolutionizing of current energy systems. With the profound effects in numerous areas of the energy system, the global focus on nanotechnology applications in the energy sector rises, making nanotechnology the future of the energy field. Nanotechnology has the potential to improve the current technologies in order to minimize the use of fossil fuels and move towards renewable energy sources (e.g. solar, wind, biomass, hydro-, and geothermal). Nanoscience brings technological innovations in energy production, conversion, distribution, storage and utilization (e.g. low-cost solar cells, fuel cells, hydrogen production, storage and distribution, thermo-electric devices, advanced catalysts and catalyst systems, new classes of batteries and supercapacitors, superconducting systems, nanotechnology-based electric cables and power lines, light and strong materials for transportation and construction, etc.).

On the road of the nanotechnology bright future stands the lack of information about its safety and potential toxicological nature. Pollutants and exposure to nanomaterials used in the energy system can cause mild to severe consequences on the environment and human health. Therefore, there are intensive studies of the possible nanoparticles' release, their behavior in the environment and the influence on humans. Moving towards green nanotechnology appears as the best approach to use the best of nanotechnology with minimal harmful influence on the environment and human health. Legal, moral, and ethical issues of nanotechnology utilization stand also on the path from nanotechnology research to commercialization and must be considered carefully before the full implementation of nanotechnology in the energy sector and any other application domain.

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