

Perspective

Graphene going green—Today’s energy scenarios

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Abstract: Nowadays, mainstream research on graphene trends towards employing environmentally friendly or green synthesis routes and precursors, and ensuing green graphene nanomaterials are shown to be highly beneficial for a range of scientific applications, from energy/electronics to engineering to biomedical arenas. Specifically, graphene has emerged as a leading contender for designing green or ecological energy conversion (solar cells, fuel cells) and energy storage (supercapacitors, batteries) devices/systems. In this perspective article, we basically aim to highlight state-of-the-art advancements of green-sourced graphene and related nanomaterials in today’s energy sectors. According to scientific endeavors so far on green graphene, its successful design, real-world energy conversion/storage device application, and commercialization depend upon resolving underlying challenges of synthesis/performance. We observe notable applications of green graphene in the fields of photovoltaics, fuel cells, capacitors, and batteries. Herein, we suggest comprehensive future surveys for advanced fabrication techniques and sustainable sources/techniques to develop next-generation green graphene-derived energy systems with superior energy storage capacities and power outputs.

Keywords: green energy; graphene; nanotechnology; sustainability; commercialization; solar cells; supercapacitors

1. Introduction

Graphene, a one-atom-thick carbon backbone nanosheet, gained increasing scientific curiosity over recent decades, therefore leading to countless literature reports on its anomalous nanostructure, properties (optical/electronic, mechanical/thermal conduction/stability, etc.), and wide-ranging practical nanotechnological deployments [1]. As per present-day growing needs of safe energy, graphene has been frequently investigated as a prominent candidate for advanced energy production/storage devices/systems and engineering-related high-tech industrial fields [2]. Despite the methodological evolution of graphene since its discovery, graphene-relying technologies seem to be continuously growing for further advanced applications, like green energy. Subsequently, recent research on graphene trends towards its ecologically benign or environmentally friendly utilizations in green energy devices [3]. Accordingly, green graphene expression is usually found valid for graphene synthesis via recyclable or sustainable materials, causing the least environmental hazards. Traditional energy devices usually employ nonecological materials/nanomaterials in their structural components as well as environmentally harmful synthesis strategies, particularly for industrial-level constructions. Herein, we note that using traditional, non-green materials and manufacturing techniques seems to be causing continuous threats to our ecosystem via greenhouse effects.

Looking at today’s green energy needs and related evolutions of graphene technologies, we planned this novel state-of-the-art perspective article to highlight the noteworthy characteristics and promising practical possibilities of graphene

nanomaterials for green energy systems. Herein, according to literature reports to date, we argue the success of substituting green graphene nanomaterials via ecological routes in energy conversion (solar cells, fuel cells) and energy storage (supercapacitors, batteries) assemblies of the current age, along with some probable limitations hindering the future commercialization of green graphene for deployments in commercial scale green energy modules. Despite the considerable scientific reports documented so far, more comprehensive investigations seemed to be indispensable for designing ecologically sustainable and functional graphene nanomaterials for future methodical and marketable green energy maneuvers. Undoubtedly, this perspective report will beneficially assist the field scientists/researchers, already struggling for innovations in ecological energy devices/systems, to judge the present state of graphene based energy safe technologies for future green energy advancements.

2. What's green energy?

Term green energy simply refers to almost all sources (sun, wind, water) for renewable energy technologies, like solar energy, biomass generated energy, wind power, hydroelectric energy, and so on [4]. Owing to the use of sustainable/renewable means, these energy production technologies usually not harm our ecosystems. In addition, green energy sources are replenished by natural processes without destroying our natural ecosystems. Undoubtedly, green energy production and uses have minimized the adverse effects of synthetic fuel/traditional energy devices on the environment by using suitable ecological substitutes. Consequently, green energy can also be named as 'clean energy' with fewer or no greenhouse emissions to the ecological system.

3. Graphene

Word 'graphene' has emerged from graphite (1986) and suffix 'ene' represents double bonds in structure [5]. It can be imagined as a single layer of graphite having one atom thick hexagonally arranged sp^2 hybridized carbon atoms in two dimensions. Eyeing the history of graphene, which seems to be connected to its initial theoretical documentation in 1947 (P. R. Wallace) and synthesis in 1962 (Hanns-Peter Boehm) [6]. Later, after several years of continuing research, a Nobel prize was awarded to Andre Geim and Konstantin Novoselov (2010) for this remarkable discovery in the nanotechnological world [1]. Afterwards, commercialization of graphene was noticed in 2014, by UK manufacturers. Predominantly, experimental and theoretical investigations on graphene have unfolded myriad of scientific applications, including energy production (photovoltaics, fuel cells), energy storage (capacitors/supercapacitors, lithium batteries), electronics (sensors, diodes), aeronautical/automobile, defense, engineering, environmental remediation, and biomedical (drug delivery, tissue engineering, biosensors), and like so, in last two decades [7]. Up till now, we note thousands of research/review articles, books/book chapters, and industrial patents in the literature reports from previous twenty years. Among notable features, graphene had transparency, electron conductivity ($\sim 200,000 \text{ cm}^2\text{V}^{-1}\text{s}^{-1}$), thermal conductivity ($\sim 5000 \text{ W/mK}$), Young's modulus ($\sim 1 \text{ TPa}$), and optical/permittivity/magnetic, and innumerable other features. For graphene synthesis,

we perceived a number of top down/bottom up processing strategies, including mechanical/chemical exfoliation, hydrothermal, chemical vapor deposition, laser/plasma approaches, and electrochemical/chemical synthesis, to mention a few, in the literature hitherto. Additional progressions on graphene can be seen in the form of surface modified graphene derivatives, nanoparticle functional graphene, and nanostructurally altered graphene into graphene nanoplatelets, graphene nanoribbons, graphene nanodots, nanoporous graphene, and related derivatives. Similarly, advanced graphene nanocomposites and hybrids have been documented with organic (polymer/carbon/nanocarbon) inorganic (metal/metal oxide/inorganic compounds) matrices and nanomaterials [8].

4. Graphene marching towards green energy

Since its discovery, graphene has been synthesized using a range of feasible techniques, involving physical means, chemical reactions, chemical vapor deposition, and many more; nevertheless, these methods need to be modified to fit the scope of green/environmental friendly and sustainable energy applications [9]. Graphene is certainly a ground-breaking nanomaterial, nevertheless normally used manufacturing techniques for its synthesis can be challenging in terms of sustainability. According to the literature up till now, graphene or its derivatives have traditionally been fabricated by adopting non-renewable carbon sources and toxic organic chemicals/reagents (hydrazine, organic solvents). Therefore, as per specific high end uses requirements, ecological graphene and graphene nanomaterials need to be designed using appropriate techniques. In particular, green graphene or graphene derived environmentally friendly materials/nanomaterials can be attained mainly via two feasible, technically successful, and frequently practiced approaches, i.e., either by using green routes and precursors for ecological graphene fabrication or surface modification of graphene to attain environmentally friendly graphene nanomaterials. Researches have focused the green graphene production through waste/green carbon precursors (plant extracts, leaves, fruits, etc.) and/or renewable carbon sources/green reducing agents/reagents in hydrothermal, chemical/physical vapor deposition, laser ablation, or alternate practices [10]. Following the search hitherto on ecologically friendly energy devices, beside graphene, environmentally friendly graphene nanocomposites have also been focused in the literature. In this concern, a number of organic combinations of graphene and polymers, especially conjugated polymers, have been scrutinized [2]. One of the most popular designs for advanced energy device components is the conducting/conjugated polymer (polythiophene, polyaniline, and others) and graphene derivative nanomaterials, having high surface area, structural durability and desirably high electrical conductivity and charge/ion/heat transportation features. However, conductive polymer/graphene systems for varying energy related device applications need to be processed by considering green/sustainability requirements of the applied precursors as well as synthesis routes. For instance, in addition to renewable/biowaste carbon precursors, use of environmental friendly solvents, like water, has been practiced to attain green graphene nanomaterials. In addition to green manufacturing tactics, formation of environmentally benign surface modified green forms of graphene, like graphene oxide, also seemed to be

advantageous towards green energy devices. According to a cautious scientific analysis, micromechanical exfoliation and modified chemical vapor deposition can be adopted as ecofriendly approaches for safe/green large scale fabrication of graphene by employing ecofriendly precursors/reagents [11].

5. Today's green energy scenarios and success of graphene

After multidecade research on graphene, its miraculous advancements seem to benefit myriad of technological fields, including energy production/storage devices and systems. Hitherto, today's green energy needs necessitate the manufacturing and use of sustainable green graphene in energy device components. Amid energy production devices, for instance, notable research attempts have been noticed regarding the implication of green graphene based technological solutions for solar cells and fuel cells (**Figure 1**). Although, graphene is a transparent, flexible, robust, and superiorly conducting nanomaterial for ideal solar cell applications, however it has meagre tendencies of current collection generated in photovoltaic devices [12]. Consequently, recent research has been noticed on the use of environmentally friendly surface modified graphene (graphene oxide, reduced graphene oxide, or other surface modified graphene forms) and nanocomposites of graphene with semiconducting polymers, in order to attain better charge collection for solar panels, to replace non-ecological electrodes like indium tin oxide, and for active/interfacial layers in solar systems. In this way, notable scientific trends depicted success of green or ecological graphene nanomaterials for organic/polymer solar cells, perovskite solar cells, dye sensitized solar cells, silicon solar cells, and allied photovoltaic device related components. Another type of technically remarkable energy production device can be termed as fuel cells. Indispensable worth of graphene has been analyzed for different types of fuel cells, including polymer electrolyte membrane fuel cells, direct methanol fuel cells, solid oxide fuel cells, and recently in the most environmentally valuable microbial fuel cell assemblies. In these fuel cells, graphene and derived nanomaterials have been exploited for electrodes (anode/cathode), electrolytes (membranes), as well as bipolar plates. Microbial fuel cell assemblies are similar to polymer electrolyte membrane fuel cells involving microorganism reliant conversion of chemical energy to electrical energy. Latest advances in ecofriendly fuel cell devices revealed remarkable uses of green synthesized graphene for anode, cathode, and proton exchange membrane in polymer electrolyte membrane as well as microbial fuel cell designs with desirably current density, power density, and power outputs. Accordingly, green graphene has been found valuable not only for manufacturing ecological non-perfluorinated electrolyte membranes, but also to design environmentally hazardous metal (e.g., platinum) or alloy free electrocatalysts and electrode materials [13]. Incidentally, green graphene technologically depicted noteworthy advances for sustainable and environmentally friendly energy conversion devices, like solar cells and fuel cells, for generating pollutant free electricity to meet current energy demands.



Figure 1. Graphene nanotechnology for green energy.

Likewise, green graphene technology also seems advantageous towards environmental friendly energy/charge storage devices, such as supercapacitors and batteries [14]. Traditionally, non-ecological materials/nanomaterials have been widely practiced for supercapacitor/battery device components. Recently, research trends towards the application of environmental nanostructures, like graphene, having inexpensiveness, non-toxicity, high structural durability, unique microstructures, electron/charge transport, specific capacitance, power/charge density, charge-discharge, and electrochemical performance for supercapacitor application. Furthermore, valuable combinations of graphene with ecological polymers (e.g. cellulose, poly (vinyl alcohol), poly (ethylene glycol), semiconducting polymers, etc.), ecofriendly methods and materials/solvents/reagents depicted noteworthy application for high-tech supercapacitor electrodes and components. Along the same lines, to replace traditional environmentally hazardous inorganic materials of lithium battery electrodes, green fabricated graphene and related nanocomposites have been essentially designed to achieve high end charge storage capacity and cyclic recital for commercial uses [15]. Herein, synergistic effects between green graphene and matrices in nanocomposites seem to play active role to design next generation technological energy storing supercapacitors and batteries. As per our analysis from literature available hitherto, advanced ecologically non-toxic fabrication techniques like three dimensional printing, spinning, coating, etc. can be used. In this way, worth of green graphene can be further enhanced for promising future energy conversion (solar cells and fuel cells) and energy storage (supercapacitors and batteries) systems. These techniques have potential to resolve limitations of environmental toxins, high production costs, non-homogeneous microstructures, and uncontrolled graphene nanomaterial production. Consequently, green graphene products can be commercialized at real world energy device level.

Nevertheless, green scale synthesis of high purity graphene is still challenging. Traditionally, major large scale production techniques for graphene include heat and chemical reduction processes demanding high temperatures, prolonged reaction cycles, and waste/pollution generation. Here, use of low temperature plasma technique

may offer competent, energy saving, and ecological solution to resolve challenging environmental effects of traditional graphene synthesis techniques.

Recent trade scale research metrics, commercial analysis data, and strategic growth estimate of graphene in energy sector up to 2030's supports the green graphene's success [16]. As per analysis, graphene market has an annual predicted growth rate of > 10%–20%, and expected to be up to 3 billion by 2030, which mainly conforms to energy sector. Specifically, this growth rate is linked to design of next generation energy storage, production, and related electronic/microelectronic devices.

We can compare the environmental advantages of green graphene vs. traditional materials in terms of recent flash joule heating technology [17]. Using this sustainable approach, green graphene can be formed from carbon rich biowastes by ~ 10 times reducing the environmental effects, like carbon emissions, cost, and life cycle energy demands, relative to conventional tactics. Thus, the recently practiced flash joule heating technology justifies circular and sustainability demands for future green high quality graphene production on commercial scale.

From societal point of view, using green graphene based renewable energy sources may result in local employment, better job opportunities, poverty elimination, and consumer choices. In addition, renewable graphene devices have valuable environmental impacts like climate change mitigation, reduced gaseous emissions, pollution free environment, and least health hazards. Nevertheless, replacing energy device components with green graphene and related techniques seemed to be challenging owing to limited reported research so far. Future advancements on green graphene based energy conversion and storage devices will be obviously valuable for high-tech aerospace, automotives, engineering and allied industries.

6. Summation

Conclusively, this perspective manuscript states the evolution of green graphene technologies in the stadia of ecological/sustainable energy conversion/storing nanomaterials and systems. Herein, we analyzed a visible nanotechnology shifting trend from traditional energy systems to green graphene-derived energy devices. Looking at today's clean energy trends, we can say that the methodological demand for graphene nanomaterials is massively increasing in industrial/commercial marketplaces due to valuable energy device-related characteristics and environmentally friendly structural and synthesis advantages. Despite scientific progress of green graphene nanomaterials so far, continuous ongoing research and future endeavors seem indispensable to resolve underlying design, properties, and performance challenges. In this manner, promising future green graphene-based systems and opportunities for industrial-level energy conversion (solar cells, fuel cells) and energy storage (supercapacitors, batteries) devices can be achieved.

Conflict of interest: The author declares no conflict of interest.

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