Chapter 15
The Economic Contributions of Nanotechnology to Green and Sustainable Growth

Philip Shapira and Jan Youtie

Abstract One of the impact promises associated with nanotechnology is that it will facilitate greener and more sustainable economic growth. We explore the extent to which nanotechnology development and commercialization is achieving this goal, drawing on secondary sources and available data. After defining the concepts of nanotechnology and green and sustainable development, we examine six nanotechnology application areas that are pertinent to green growth and sustainability. These application areas are assessed relative to their scale and scope through market forecasts, green benefits and potential issues and limitations. These six application areas are: nano-enabled solar cells, energy storage, nanogenerators, thermal energy, fuel catalysis, and water treatment. Nanotechnology-enabled applications in these areas offer potential benefits, such as reduced costs, less toxicity, greater efficiency, operating frequency, voltage, reduced complexity, and reliability. However, many sales forecasts associated with these applications have been adjusted downwards not only as a result of the economic downturn in the first decade of the 2000s but also due to the limited value offered by these nanotechnology-enabled application compared to what is already on the market (the incumbent technology). We find that while green nanotechnologies have the potential to make contributions both to addressing green challenges and to fostering sustainable economic development, development and diffusion is taking longer than previously anticipated, and in some cases the promised scale of benefits is unlikely to be realized. Additionally, the potential life cycle environmental overheads of some complex engineered nanomaterials must be taken more fully into account in assessing net contributions to green growth.

Keywords Nanotechnology • Green growth • Sustainability • Life cycle assessment

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15.1 Introduction

Green nanotechnologies have attracted recent attention in discussions about how nanotechnology can address societal grand challenges. This paper identifies and discusses a range of specific applications of nanotechnology to green and sustainable growth, focusing especially on the use of nanotechnology in sustainable energy production and use, water provision, and other environmental applications.[1] The global demand for energy is estimated to increase by more than 30 % from 2010 to 2035 [1], while more than 800 million people worldwide currently are without access to safe drinking water [2]. The development of affordable and safe ways of meeting these needs has never been more pressing, further bolstered by fluctuations and uncertainties in markets and the reliability of supplies and by demands to reduce carbon emissions and other environmental impacts. While requirements for new energy sources and clean water are particularly pressing in non-OECD countries, developed countries also need to find ways to sustainably fuel and support their people and economies. These challenges drive interest in the applications of nanotechnology both to improve existing technologies and to offer new alternatives.

The paper considers examples of the possible scale and scope of contributions of nanotechnology to energy production and use, water provision, and other environmental applications. It provides some insight into how the economic contribution of nanotechnology to green and sustainable growth might be conceptualized and valued. Questions about potential issues and risks are also raised. The paper begins with a review of how nanotechnology in general, and green nanotechnology in particular, have been defined. This is followed by discussion of green nanotechnology applications, market forecast examples, and indicators of economic impact. Our concluding remarks stress the importance of assessing the economic impact of nanotechnology from a life-cycle perspective that considers the full range of economic, environmental, and societal implications.

15.2 Definitions

It has been suggested that green nanotechnology will allow us to make and use products “with the environment in mind” [3]. This could include using nanotechnology to make solar cells more efficient in generating renewable electricity or more

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effectively cleaning polluted water. But what is nanotechnology? And, what makes a particular application of nanotechnology green?

To consider the first question, the US National Nanotechnology Initiative (NNI) highlights size, novelty, and human manipulation in its definition of nanotechnology.

> Nanotechnology is the creation and utilization of materials, devices, and systems through the control of matter on the nanometer-length scale, that is at the level of atoms, molecules, and supramolecular structures. The essence of nanotechnology is the ability to work at these levels to generate structures with fundamentally new molecular organization. These "nanostructures" … exhibit novel physical, chemical, and biological properties and phenomena ([4], p. iii).

Other official organizations have proposed similar types of definitions of nanotechnology, with some variations by nanoscale dimensional lengths (see, for example, [5], pp. 5–6; also [6]). Nanotechnology is frequently characterized at the length scale of 1–100 nm (with 1 nm equivalent to one billionth of a meter). Several bibliometric definitions have arisen to delineate scientific research in nanotechnology. Based on academic journal articles, researchers have used a range of methods to portray nanotechnology research. For example, Porter and colleagues use a two-stage Boolean search strategy comprised of keyword based search terms for nanomaterials, nano-processes, and instruments heavily used in nanotechnology; a second stage follows in which articles defining nanotechnology based on size alone are excluded [7]. In contrast, Zitt and Bassecoulard [8] use a citation-based approach for field definition. Across most of these definitions, the studies have found nanotechnology to be highly multidisciplinary, centered on materials science, physics, and chemistry, with biomedical fields comprising a growing share of research publications [9, 10]. In addition, there is evidence that nanotechnology has early characteristics of a general purpose technology, which suggests that nanotechnology has the potential to enable future waves of technological and economic innovation [11].

These scientific definitions fit less easily into commercialization characterizations, however. While nanotechnology has applications across multiple industries, there are no standard classifications of nanotechnology developing or using sectors. This has given rise to the use of various patent classes (including nanotechnology "cross-classes" such as International Patent Class B82, the Japanese Patent and Trade Office Class ZNM, the US Patent and Trademark Office (USPTO) Class 977, and the European Patent Office Class Y01N), product inventories, and case studies to determine the extent to which companies and products are indeed engaged in nanotechnology [12]. Companies and countries vary in practices to indicate whether products and processes are nano-enabled. With limited requirements to declare the use of nanotechnology through labeling or other disclosures, much remains unknown about the scale and scope of nanotechnology in commercial sectors.

The second question, about the nature of green nanotechnology, adds a further level of complexity. There is much diversity about what a green application is and green growth is arguably an even harder concept to measure and track than nanotechnology per se. One approach to understanding greenness is by focusing on outcomes and identifying how nanotechnology is contributing to sustainability targets. The OECD Green Growth Strategy, for example, promotes economic growth and development alongside the preservation of natural assets and the environment [13].

Yet there is diversity in targets and strategies among member countries. For example, Korea has set an emission reduction target of 30 % reduction in greenhouse gas emissions by 2020 over base year 2005 estimates and is seeking to meet this target through voluntary commitments and measures to allocate 2 % of GDP to green growth in the country's 5-year plan. Ireland's National Development Plan [14] addresses waste management, transportation, sustainable energy, and climate change and environmental research through investment plans amounting to a €25 billion (2007–2013). China's Twelfth Five Year Plan includes six green pillars: resource management, closed-loop economics, environmental and ecosystem protection, water conservation, disaster recovery, and climate change. The plan includes several emission reduction targets, for example a 17 % reduction of carbon per GDP unit by 2017 [15].

The OECD has itself promulgated indicators for measuring green growth milestones. These indicators recognize innovation as a key to green growth but it requires multidisciplinary involvement from fields outside energy and environmental domains, absorptive capacity through human capital and trade and foreign direct investment, and collaborative intellectual property mechanisms to scale-up diffusion in developing countries. Monitoring green growth strategies involves the development of indicators of the environment and resource productivity of the economy, natural asset base, environment health risks as well as services and amenities, economic opportunities and policies in regulation and other areas, and socioeconomic context [16]. Measuring the contribution of nanotechnology to the achievement of these indicators across these broad categories would be a major undertaking, with information requirements that would be problematic to satisfy particularly if multi-country or global benchmarks are sought.

Another approach to assessing nanotechnology's contribution to green growth and development is by looking at the production system—the means and processes of green growth rather than the ends. For instance, there have been attempts to define green industries and sectors. The US Bureau of Labor Statistics [17] proposed two approaches to measuring green industries and occupations. The narrower output approach identifies establishments that produce green goods and services. These are goods or activities which have favorable impacts on the environment. The broader process approach identifies establishments that utilize environmentally friendly production processes based on worker responsibilities. These definitions result in five broad groupings: (1) energy from renewable sources, including wind, biomass, geothermal, solar, ocean, hydropower, and landfill gas and municipal solid waste, (2) energy efficiency, including energy-efficient equipment, appliances, buildings, and vehicles, as well as products and services that improve the energy efficiency of buildings and the efficiency of energy storage and distribution, such as Smart Grid technologies, (3) pollution reduction and removal, greenhouse gas reduction, and recycling and reuse, (4) natural resources conservation, including organic agriculture and sustainable forestry; land management; soil, water, or wildlife conservation; and storm water management, and (5) environmental compliance, education and training, and public awareness. The former four comprise businesses with a more technological orientation.

This approach is consistent with the definitions promulgated by the United Nations and OECD. The United Nations Environment Program defines green jobs as "positions in agriculture, manufacturing, construction, installation, and maintenance, as well as scientific and technical, administrative, and service-related activities, which contribute substantially to preserving or restoring environmental quality. Specifically, but not exclusively, this includes jobs that help to protect and restore ecosystems and biodiversity; reduce energy, materials, and water consumption through high-efficiency and avoidance strategies; de-carbonize the economy; and minimize or altogether avoid generation of all forms of waste and pollution" ([18], pp. 35–36). OECD research concludes that "green jobs span a wide array of skills, educational backgrounds, occupational models, and can be found at any point on the supply chain of what are considered to be green firms or business" ([19], p. 21).

A complementary approach to identifying potential green nanotechnology applications is offered through patent records. Patent filings indicate inventions that promise novelty and utility. While only a subset of granted patents subsequently have innovation value, trends in patent applications and grants can help in signifying technological trajectories and corporate intellectual property strategies in emerging domains. As already noted, patent offices in the USA, Europe, and Japan have developed cross-classes for defining nanotechnology. Technometric search strategies have also been used to identify nanotechnology patents [7]. Additionally, patent offices and databases have developed green patent classes that address many of the areas already specified. The USPTO's definition of green patent classes in its Green Technology Pilot Program (to provide accelerated review of patents related to green technologies) encompasses alternative and renewable energy production, energy storage (batteries and fuel cells), energy distribution (including "smart grid"), energy conservation and efficiency improvements, greenhouse gas reduction, carbon sequestration, environmental purification, protection or remediation, and environmentally friendly farming [20]. The World Intellectual Property Office has a definition of green patent classes that encompasses similar categories of "environmentally sound technologies": alternative energy production, transportation, energy conservation, waste management, agriculture and forestry, administrative, regulatory or design aspects, and nuclear power generation [21]. Derwent World Patents Index also codes green patents based on a set of technology manual codes [22].

Several studies have addressed the overlap between nanotechnology and green applications. Strumsky and Lobo [23] examine the subset of USPTO that fall in nanotechnology cross-class 977. Nine percent of nanotechnology patents are classified as green technologies, based on this definition. The authors find that green nanotechnology patents have the same number of inventors as the average green patent but more claims, more citations received, and more technology codes, suggesting that these patents are substantially more inventively novel than the average green patent. Lux Research [24] reported that nanotechnology comprises 5 % of government investment in green technology, 24 % of publications related to green science and technology research, 15 % of green patents, 19 % of cleantech startups, and 15 % of venture capital devoted to green technology.

15.3 Green Applications of Nanotechnology

Consideration of the overlap between green and nanotechnology application has attracted increasing attention and investment. In the USA, nanotechnology for solar energy collection and conversion was one of three signature initiatives in the NNI's 2011 strategic plan. This area was comprised of research investments in seven different areas: (1) conversion efficiency (photovoltaic, thermophotovoltaic), (2) solar thermal, thermal conductivity, (3) nanoparticle fluid, heat transfer, (4) thermoelectric, (5) solar fuel, (6) solar characterization, and (7) energy storage [25]. This initiative received 3.7 % (US$68.8 million) of the overall NNI budget and the proposed budget for fiscal year 2012 called for the budget to nearly double and account for 5.9 % of the NNI budget.

Green nanotechnology also plays a central role in future roadmaps for the larger nanotechnology field. A recent example is Nanotechnology Research Directions for Societal Needs in 2020 ("Nano 2")—which included a prospective outlook component engaging a wide range of US researchers, companies, analysts, and other stakeholders along with expert workshops in Europe and Asia [26]. A central element of this future vision concerned green nanotechnology, with particular attention given to several areas for nanotechnology emergence: (1) nanostructured photovoltaics (organic, inorganic), (2) artificial photosynthesis for fuel production, (3) nanostructures for energy storage (batteries), (4) solid state lighting, (5) thermoelectrics, and (6) water treatment, desalination, reuse.

These green nanotechnology areas can be better seen through a presentation of illustrative applications and research areas. Nano-enabled solar cells use lower cost organic materials (as opposed to current photovoltaic technologies which use rare materials such as platinum) to convert solar energy. In addition, nano-enabled solar cells can be less expensive to produce. Examples include die sensitized solar cells, which use dye molecules, which take in sunlight, over a scaffold of titanium oxide nanoparticles. Copper zinc tin sulfide based solar cells represent another approach that uses less rare and toxic materials for photovoltaic solar electricity generation. The biggest limiting factor in current nano-enabled solar cells is the need for efficiency and lifetime (i.e., stability of materials) to be on par with conventional inorganic-based photovoltaics [27]. For inorganic photovoltaics, nanostructures have been used through colloidal synthesis to increase photovoltaic performance. In addition, nanostructuring can reduce charge travel distances, allowing the use of less costly materials.

Nanogenerators use piezoelectric material such as zinc oxide nanowires to transfer human movement to energy. By stacking of deposits of millions of nanogenerators on polymer chips, it could be possible to generate the energy equivalent of AA batteries. Self-powered sensors, wearable devices, and implantable energy receivers are examples of nanogenerators applications [28].

Energy storage can be viewed in terms of the use of nanotechnology for improvements to existing batteries and nano-enabled fuel cells. Many current batteries use lithium-ion technologies. Nanoparticles offer improvements such as quicker recharging capability and greater shelf life. Research into printed batteries suggests that electrolyte components of a battery can be thinly layered with nanotube ink, eventually producing a battery that can be used with disposable products such as Radio-frequency identification (RFID) tags and certain applications that require greater power [29]. Fuel cells face a barrier in their use of rare platinum materials to act as catalysts for generating electrical currents. Nanotechnology plays a near-term and longer-term role concerning these catalysts. In the nearer term, nanomaterials are used to improve the performance of platinum-based electrocatalysts. Longer term directions point toward non-platinum electrocatalysts composed of nanocomposites that are less expensive, more stable and durable, and have greater efficiency [30].

Thermal energy applications of nanotechnology include not only improvements in energy sources but also insulation. Nanoparticle coatings are widely used on glass to provide UV protection, self-cleaning capabilities, and water resistance and are also available in paints. Vacuum insulation panels are expected to be among the major uses of nanoporous aerogel and nanoparticulate fumed silica [31].

In fuel catalysis, nanoparticles are used in production, refining, fuels, and automobile emission reduction. Dewaxing compounds for lubricants and low sulfur fuels are provided through shape selectivity features of certain molecules. High silica, porous zeolites are used for support for catalytic converters. Molybdenum disulfide and copper–zinc oxide particles have application in removal of sulfur and hydrogen in mixed fuel stocks from diesel or methanol sources. Future platforms for energy conversion and biofuel processing are long-term applications of nanotechnology in fuel catalysis [32, 33].

The provision of safe drinking water has been a major area for nanotechnology research. Nanotechnology-based solutions to water shortage issues involve treatment, desalination, and reuse [34]. Nanoabsorbents (such as nanoclays, zeolites, metal oxide nanoparticles, nanoporous carbon fibers, and polymeric adsorbents) can eliminate particulates from contaminated water. Toxic organic solutions can be converted into nontoxic by-products through nanocatalysts and redox active nanoparticles. Bacteria can be deactivated without creating by-products through the use of nanobiocides. Carbon nanotube filters, reverse osmosis membranes using zeolite nanocomposites and carbon nanotube membranes, and polymeric nanofibrous membranes have been used for water treatment and desalination. Dendrimer-based ultrafiltration systems and nanofluidic systems have used low-pressure membrane systems to remove ions from water solutions [35]. Photocatalytic methods using UV-light to irradiate pollutants is another example of the use of nanotechnology in this area, with nanoparticles such as titanium dioxide and zinc oxide used as the photocatalyst [36].

15.4 Market Forecasts: Examples

There are four main issues with forecasts of green nanotechnologies. Green industries and nanotechnology have been characterized as platform technologies which to date have exhibited evolutionary patterns of development while, many early forecasts suggested steeper growth trajectories. Some of these growth trajectories now appear aggressive because large shares of the sectors in which nanotechnology is deployed are attributed to the estimate. For example, the 2001 forecast of nanotechnology's global market size of US$1 trillion by 2015 was first introduced in Roco and Bainbridge [37]. This estimate is based on the total anticipated manufacturing, electronics, health care, pharmaceuticals, chemical processing, transportation, and sustainability improvements arising from nanotechnology. Sustainability improvements were estimated at a savings of US$100 billion a year for 10–15 years based on nanotechnology-enabled lighting. This estimate also indicated a 200 billion ton reduction in carbon emissions from nanotechnology-enabled lighting. Lux Research's 2007 estimates of the size of the nanotechnology market also assumed a steep growth trajectory to US$2.6 trillion by 2014. This estimate was more than 70 % higher than Lux's earlier 2005 report estimate [38, 39].

Overly optimistic forecasts may also be possible in that the full sales of products with a small nanotechnology contribution may be attributed in a green nanotechnology forecast rather than apportioning out the true nanotechnology part of the product, which indeed may be very difficult for some products that use nanomaterials and processes. Nanotechnology's contribution may emerge from incorporation of nanomaterials, processes or instruments used to develop nanomaterials, and even the science itself that has developed around nanotechnology. These potential contributions may be over-estimated or even under-reported (in that there is difficulty in linking advances in a field of science to an application). In looking at the size of the nanomaterials market relative to the size of the overall estimates for nanotechnology, one can see that the former is much smaller than the latter. Lux Research's estimates of nanomaterials versus products from these materials (through nanointermediaries and nano-enabled products) published in 2005 suggested that nanomaterials would comprise only 0.5 % of product sales or US$3.6 billion (by 2010) out of a total global nanotechnology market estimate of US$1.5 trillion [38].

The economic downturn since 2008 has caused some downward adjustment in these market forecasts. Lux Research's 2009 global nanotechnology market forecast was decreased to $2.5 trillion by 2015, 4 % less than the 2007 estimates. Declines in the automobile and construction industries were also estimated to affect market demand for nanomaterials and composites [40].

Finally, the viability of forecasts relates to the extent to which the technology will be able to produce significant benefits over and above what is already on the market. These benefits include not only lower costs but other factors as well, such as efficiency, operating frequency, voltage, reduced complexity, and reliability and lifetime.

A summary of available forecasts for selected green nanotechnology products generally presents a picture of moderate estimates of potential market size on a global basis (see Fig. 15.1). It should be noted that some of these forecasts are for specific and targeted green nanotechnologies. We have examined a number of selected green nanotechnology applications in more detail. For each technology, we consider benefits relative to green growth and potential market size forecasts. Issues in estimating application market size are noted as are barriers to achieving nanotechnology contributions to green growth. (See also Table 15.1 for a summary of these

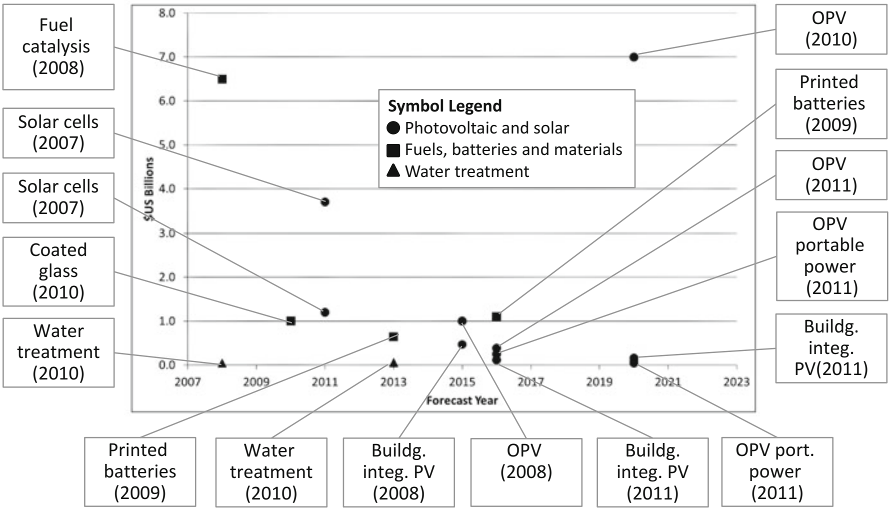

Fig. 15.1 Global sales forecasts—selected green nanotechnologies. *Sources*: Cientifica [41]; Lux Research [24, 40]; BCC Research [42]; Global Industry Analytics [43]. Year of estimate in parentheses. PV = Photovoltaic; OPV = Organic Photovoltaic

Table 15.1 Selected nano-enabled green applications: benefits, global market estimates, and issues

Application	Green benefits	Market estimate (worldwide)	Issues and challenges
Nano-enabled solar cells	Lower cost, less toxic, more abundant materials	US$1.2 billion for 2011 (2007 estimate)	Nano-enabled solar cells must be able to reach performance and cost levels of existing non-organic PVs
Energy storage	Improved performance of existing materials (e.g., quicker recharge, greater shelf life) and long-term use of new less expensive, more stable and durable, and efficient new materials	US$3.7 billion in 2011 (2007 estimate)	Substitutes for rare materials not yet technologically available.
Nanogenerators	Self-powering of small electronic devices	See energy storage estimates.	Application of nanogenerators awaits market commercialization
Thermal energy	Integration into existing materials for greater insulation, UV protection, water resistance.	Aerogels: US$140 million (2012 estimate)	Cost of these materials compared to traditional building materials is an issue. The strong integration of nanotechnology into the existing product makes it difficult to separate the contribution of nanotechnology

(continued)

Table 15.1 (continued)

Application	Green benefits	Market estimate (worldwide)	Issues and challenges
Fuel catalysis	Greater efficiency and performance in fuel use	US$5–US$8 billion a year as of 2008	Assumes that nanotechnology derived synthetic methods can be applied to the full fuel catalysis market
Water treatment, desalination, reuse	New clean, safe water sources	US$6.6 billion in 2015	Market is in developing countries while technological leadership is in developed countries plus China. Potential environmental, health and safety concerns may limit commercialization.

Note: See text for sources and further discussion

selected nanotechnology applications and their benefits relative to green growth.) The selected green nanotechnology applications are broadly in energy, water, and related environmental domains and are discussed below.

Solar cells and photovoltaics. Nanotechnology-enabled solar cells and photovoltaic applications are frequently highlighted as potential growth markets. Lux Research's [24] estimate of the global market for nano-enabled solar cells for 2011 was US$1.2 billion. However, promised performance relative to cost advantages have yet to fully materialize. Additionally, the price of conventional silicon solar cell panels has continued to fall in recent years as manufacturers (particularly those based in China) have expanded increasingly efficient production facilities [44]. The segment of this market concerning organic photovoltaics (OPV) is illustrative. Earlier reports from 2007 and 2008 projected significant growth for the OPV market. These reports acknowledged the underlying technological challenges of OPV, but they believed market growth would result from substantial technological improvements and the low comparative costs for OPV compared to conventional PV. According to these reports, these advances, at least partially, would be supported by dramatic increases in venture capital investments and policy initiatives from the US Department of Energy's Solar Technology Energies Program. NanoMarkets [45] projected the 2015 worldwide market for organic photovoltaics to grow to US$1 billion, driven by a projected US$470 million building-integrated photovoltaics (BIPV) market. However, these technologies have not advanced in the marketplace by as much as earlier reports had anticipated. Technology challenges present significant obstacles to commercialization and future market growth. Conversion efficiency for OPV cells is expected to continue to increase, but the technology will not be able to compete with conventional silicon-based photovoltaics for some time. Additionally, costs—the widely cited advantage of OPV versus traditional PV technologies—continue to be a challenge. As conventional PV technologies have seen rapid decreases in costs, some reports find that OPV is losing its cost advantage [46].

To successfully commercialize, OPV technology must overcome significant conversion efficiency, lifetime, and cost barriers. Given these continued challenges, by 2011 market researchers were taking a much more conservative outlook for OPV. Recent market reports believed future growth of OPV applications would be limited to specific product segments, such as portable power, where flexibility and low costs are necessary and efficiency and lifetime are less important. Until efficiency, lifetimes, and costs can compare with conventional PV technologies, OPV will not compete with other PV product segments. NanoMarkets, which in early 2008 expected the OPV market to grow to $1 billion by 2015, revised its forecast to $387 million by 2016 [47]. Rather than building-integrated photovoltaics, portable power is now expected to drive more modest OPV growth. OPV portable power, for which the technology's challenges of efficiency and lifetime are not major concerns, is projected to grow to $250 million by 2016. Potential growth for BIPV, however, remains limited by the technology challenges, as well as an overall decline in construction with the most recent recession. Nanomarkets subsequently projected BIPV to be much slower to grow in popularity, with only $113 million in revenue by 2016 [47]. Lux Research shares a similar, but less-optimistic view about OPV growth. Citing that conventional PV manufacturing costs continue to decrease, the report forecasts the entire OPV market to grow to only $159 million by 2020. Like NanoMarkets, Lux Research (in Energy Weekly News [48]) believes this growth will be driven by portable power, primarily used in the defense industry, and by BIPV applications. With this forecast, these two segments will account for approximately $80 million and $44 million of the entire market, respectively.

Energy storage. Nanotechnology in energy storage in 2007 was estimated to be a US$3.7 billion market by 2011 according to Lux Research. Printed batteries for energy storage are an enabling component for other organic electronic applications, including RFID tags, smart cards, and sensors. With the growth of these applications, industry analysts project revenue from printed batteries to exceed US$1 billion by 2016 [49]. Despite printed battery's potential for widespread commercialization, analysts note that the cluster faces significant funding and investment hurdles before the technology can fully develop and be used in these other applications [50]. *Nanogenerators* have yet to reach the market in a significant commercial way. Limited commercial activity for this technology makes it difficult to estimate the size of the market. Estimates associated with the energy storage market are likely to be most applicable.

Thermal energy. Nanotechnology in the thermal energy domain has diverse applications that are lighter and reduce the porosity of building materials and make them more energy efficient. Aerogels, a nano-structured solid foam that substitutes for denser foam-based insulation, was projected to increase in global market size from about $140 million in 2012 to more than $330 million by 2017 [51]. The primary uses are for insulation in gas and oil pipes, medical devices, and aerospace rather than insulation in building construction. Other applications, such as nanocoating of flat glass for thermal control, are penetrating high-performance construction market sectors [52]. Yet the relatively high cost of these materials, relative to conventional building materials for insulation and coated glass, is a barrier to entry. Similarly constraints to the adoption and penetration of nano-coated glass in the automotive industry include cost and the ability to incorporate machines and skills into production lines.

Fuel catalysis. Fuel catalysis is a major area for nanotechnology application. Nanotechnology derived synthetic methods have been estimated to be used in 30–40 % of global fuel catalysis products representing US$18–20 billion a year. However, the extent to which this share of the fuel catalysis market that can be claimed as a direct effect of nanotechnology is debatable [33].

Water and water treatment. There is significant need in developing countries for clean, safe water, especially in rural areas, as well as in rapidly expanding mega-cities, and this is a significant potential market. Worldwide, more than 0.8 billion people are without access to safe drinking water, with 2.6 billion people lacking improved sanitation facilities [2]. This imposes high human, environmental, and economic costs. Nano-engineered structures, membranes and crystals have been put forward for water disinfection and cleaning as well as for desalination [53]. The market for nano-enabled water and wastewater applications is predicted to reach $6.6 billion by 2015, up from $1.6 billion in 2007. Nano-enabled applications are said to have energy-saving advantages over conventional approaches. For example, current desalination techniques (such as reverse osmosis) require significant amounts of energy. Less energy-intensive nanotechnology-enabled applications have been proposed, including using desalination batteries with sodium manganese oxide nanorods and silver electrodes to generate drinking water from seawater by extracting sodium and chloride ions [54]. Developed countries (such as the USA, Germany, and Japan) are considered to be developing the most advanced nano-enabled water treatment technologies, although China also is developing capabilities. The greatest needs are in rural Asia, Africa, and Central and South America. The disjuncture between the location of capabilities and areas of greatest need could limit opportunities for the commercialization of nano-enabled water treatment technologies. This is not only because of knowledge and market demand gaps but also because of potential concerns (validated or not) in the sending (developed) as well as receiving (developing) countries related to the environmental, health, and safety implications of nano-enabled water treatments.

15.5 Indicators of Economic Impact

There are several ways of approaching the question of the economic impact of green nanotechnologies and indicators to assess those impacts. This section considers how direct and indirect economic impacts can be conceptualized. We also highlight potential indicators of impact and discuss issues and cautions associated with the application of those indicators.

The market studies discussed in the previous section suggest that there are major potential markets for green nanotechnologies. However, investment, including in research, technological development, production, testing, marketing, standards setting, regulation, user adoption, and monitoring needs to occur before these markets can be realized. The range of public and private capital and ongoing costs associated with the application of green nanotechnologies needs to be offset against benefits, taking into account such factors as the timing and distribution of various benefits and costs, interest rates and opportunity costs, and the relative advantages of green nanotechnologies compared with conventional applications. In the process of producing and using green nanotechnology products, there are likely to be a series of indirect effects, including on supply chains and other spillovers to third parties and the environment. Not all of these benefits and costs will be measurable, and some impacts (including health, safety and environmental impacts) may not be apparent (or known not to be an issue) until years after initial use.

Simple analyses of the economic contribution of green nanotechnologies would give consideration to the net costs of technological development and market entry relative to the value of the outputs and outcomes achieved, taking into account considerations of time and perspective (or standing). The net costs include such inputs as public R&D, knowledge development, and facilities costs, private industry R&D costs, and prototyping, testing, commercialization, production start-up, and marketing costs. The outputs of such expenditures can include contributions to science and knowledge, generic or specific technologies developed, intellectual property development (including patents and licenses), standards development, and new company start-ups. These outputs can have intermediate economic value, but the greatest economic potential is through outcomes such as profitable sales from new products, increased productivity and other process improvements, savings of costs that would otherwise be incurred, employment and wage generation, and benefits to consumers and users. These outcomes can lead to developmental and public benefits including contributions to national and regional gross domestic product, improved competitiveness and balance of trade, and environmental and other societal benefits. There can also be strategic benefits in the use of nanomaterials, for example to reduce reliance on rare metals and materials sourced from overseas locations. However, standing is critical: the relative weight of benefits and costs of a new technology may vary according to whether the perspective is that of a producer, competitor, customer, worker, industry, region, or country.

Policymakers are often especially interested in the economic development effects of new technologies, such as green nanotechnologies, including impacts on jobs and wages. Employment will be generated through research, manufacturing, delivery, use, and maintenance related to green nanotechnology products and processes, and associated industries and services, although predicting the number of new jobs is difficult. Existing workers may shift into green nanotechnology activities as conventional products are replaced. It is also difficult to define what is a nanotechnology job or a green job, let alone what is a green nanotechnology job. Nanotechnology is a broad platform technology, it cuts across multiple industrial sectors, and frequently represents a small proportion of other downstream products, raising issues of the unit of analysis. Hence wide ranges are seen in estimates of nanotechnology jobs. US estimates of nanotechnology jobs have varied from tens of thousands today

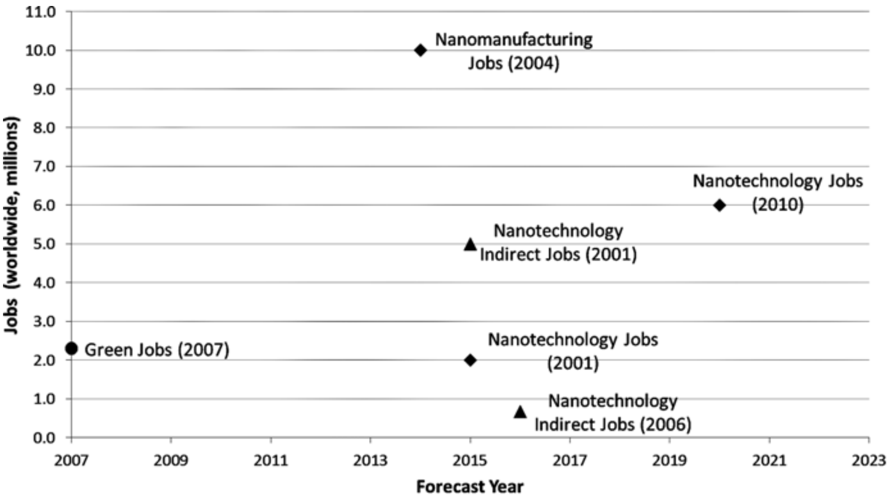

Fig. 15.2 Nanotechnology and green jobs—selected worldwide forecasts. *Sources*: Invernizzi [55]; UNEP [18]. Year of estimate in parentheses

to close to one million by 2015, with worldwide estimates of nanotechnology jobs (see Fig. 15.2) apparently diminishing from earlier estimates of ten million (in manufacturing) in 2014 to six million by 2020 (see also discussion in [55]). Green nanotechnology jobs will employ a significant share of the nanotechnology workforce, depending on the share designated as green, with potentially a share of other green sector jobs again depending on the definitions used (for recent attempts to define and measure green jobs, see [17, 18, 56]). Not all nanotechnology jobs will be well-paid, and there will likely to be some offset in employment as certain conventional products and skills are replaced [55].

A further reason why it is difficult to predict jobs related to nanotechnology, including green nanotechnology, lies in the often lengthy time scale for the economic development benefits of emerging technologies to materialize. Different kinds of cost and benefits usually occur differentially over time. For example, R&D costs typically occur early in the cycle of a new technology, although there may well be ongoing R&D costs as the technology is continuously improved and adapted. Similarly, as Tassey [57] notes, various benefits can occur at different time scales. In the short-term, intermediate outcomes such as patents, R&D partnering, prototyping, and the attraction of venture capital may occur; in the medium-term, new products and processes and company growth may be seen; while it is in the longer term that broad industry, economic and societal benefits appear. The definition of these terms (by years) varies by the technology and market acceptability. Nanotechnology R&D began to take off in the mid-1990s, with big boosts in public R&D from the 2000s onwards [58]. After more than a decade of significant worldwide public and private R&D, and many scientific and technological achievements [26], most nanotechnologies are arguably still at early stages of development. Cost–benefit analyses conventionally discount future costs and benefits to today's values, using the current interest rate or alternate (often higher) hurdle rates of return.

A well-elaborated example of a comparative method for assessing the economic value of nanotechnologies is provided by Walsh et al. [59] in a study for the UK Department for Environment, Food and Rural Affairs (DEFRA). This study delineates a methodology for estimating the net value-added of a nanotechnology innovation, which is defined as the difference between the value-added of the nano-enabled product and that of the comparable incumbent product. It assumes that that there are conventional incumbent products against which new nanotechnology products can be matched. The net value added is comprised of three elements: producer surplus (sales less costs) plus consumer surplus (consumer value less price); plus other externalities (net benefits to third parties). A multistep process is employed which involves defining the nano-enabled product, identifying its use and function, identifying a comparable incumbent product, determining the production costs of the nano product and its comparator, determining sales prices, identifying the nano-product's effect on the market, determining externalities (including net environmental benefits and R&D spillovers), and calculating producer surplus, consumer surplus, and externalities. Market scenarios are identified where the incumbent product is replaced with the new product but with variations as to whether the market size is unchanged or increased and whether functionality is increased, with consumer surplus a function of price declines and improved performance for the nano product relative to the incumbent. The approach further allows geographic allocation of producer surplus and externalities (where location of production differs from location of consumption). The model considers the "phase-in" time of the product (diffusion time) using an S-curve model. Discount rates are applied to adjust future expected cash flows to present values. The rate is comprised of two parts: a normal (or risk free) component accounting for expected inflation; and a premium that discounts the probability that the product may not successfully reach the market. Walsh and colleagues apply their approach to several green nanotechnology cases studies, including nano-enabled food packaging, thin-film photovoltaics, fuel catalysts, amperometric electrochemical gas sensors, nano-enabled antifouling paints, and nZVI technology [59]. The case studies illustrate that net economic benefits are relatively small where the nano-enabled product has limited advantages over incumbent products and market size is unchanged; larger benefits accrue where the nano product reduces costs compared with the incumbent, markets are expanded, and diffusion is relatively rapid (Table 15.2). The cases studies take a national perspective. For the UK, economic externalities are reduced for some technologies because R&D, materials production, or manufacturing are overseas. In the main, net benefits are estimated for UK markets (which are a relatively small share of potential global markets). Environmental benefits and costs outside of the UK are not included in the analyses (although they are mentioned). The authors recognize that there are significant uncertainties in the forecasts of markets and nanotechnology penetration. It is also noted that environmental impacts often cannot be reliably monetized, and that current evidence is inconclusive on some potential environmental impacts. Subsequent findings of health or environmental harm would negatively change the calculated benefit–cost ratios.

This kind of approach to estimating economic value is instructive, but it is sensitive to the assumptions and discount rates used and there are a series of caveats. The comparative approach assumes that nanotechnology innovations do not offer

Table 15.2 Summary of DEFRA case studies of economic value of innovation in green nanotechnologies in the UK

	Gas-impermeable nano-clay film	Thin film photovoltaics	Fuel-enhancement catalysts	Gas sensors	Antifouling paints	Nano zero-valent iron
Application	Food packaging	Energy production	Fuel additive	CO gas detection	Ship building	Remediation of contaminated sites
Incumbent product	Plastic film	Crystalline silicon photovoltaics	Diesel fuel	Electrochemical sensor	Foul release paints	Pump and treat
Market scale	80.32 m (10 g) units/year (UK)	250 MW/year (UK)	25 b liters/year (UK)	823,000 households/year (UK)	£2.3 m (UK). Possible export sales of £143 m over 20 years	40 sites/year (UK)
Market characteristics	Fixed (no unit growth)	Fixed (no unit growth)	Total sales of diesel (UK)	6 year replacement	5 % of merchant ships	10 % of contaminated sites
Nanotechnology product advantage	Reduced household food waste by 2 % annually	Reduced CO_2 by half over silicon based PV	Improves fuel efficiency by 5 %	Increases performance per unit mass, or reduces the mass required	1 % improvement in fuel efficiency	25–30 times faster reaction rates
Price differential	+10 % for nano product	+36 % higher than the incumbent	14–20 % higher for nano product	5–10 % below incumbent price	Initially 24 % higher, then matching incumbent over time	90 % lower for nano product
Benefits (surplus) to producers	£11.41 m/year	£1.75 m/year	£50.82 m/year	£1.24 m/year to £0 m/year	£0.34 m to −£0.074 m/year	−£0.365 m/year

Benefits (surplus) to consumers	£0.60 m/year	£7.89 m/year	£1,142.5 m/year	£0.1 m/year to £0.35 m/year	0–£398,000/year	£136 m/year
Economic Externalities	£122.85 m/year household savings	No R&D externalities to UK	£1.44 m/year	No R&D or other externalities anticipated for UK	£0.6 m to £0.7 m/year	No additional externalities identified.
Environmental Externalities	Reduction of 243,000 tonnes of CO_2 e/year (=£5.36 m at DECC carbon price)	Reduced CO_2, NOX, SOX emissions; fewer heavy metals then conventional PV	0.111 kg of CO_2 per liter of fuel consumed	None in UK. Reduction in platinum mining overseas.	8,640 tonnes of CO_2/year (UK)	No conclusive evidences. Impacts of nanoparticle release not known.
Diffusion rate	50 % UK market share = 8 years	100 % UK market (full replacement of silicon PV)	50 % UK market share = 8 years	66 % UK market = 8 years	50 % UK market share = 8 years	50 % UK market share = 8 years
Net present value to UK economy	£4.941 b (20 years)	£205 m (20 years); negative £1.1 b 20-year value with tariff subsidies	£15.3 b (20 years)	£12.4 m (20 years)	£2.3 m (20 years)	£2.4 b (20 years)

Source: Walsh et al. [59] (cases in main report and in supplemental working guide) in report for the UK Department for Environment, Food and Rural Affairs (DEFRA)

Note: m = million; b = billion

completely new functionalities and that matching conventional products can be found. The approach also works best with one nanotechnology innovation and one function at a time. Indirect effects, for example on suppliers, are not included. Nanotechnology product prices are assumed to decline over time (although this assumption can be modified). Where data is not available, proxies are used, which may or may not be accurate. Environmental impacts can be included as externalities but only where they can be foreseen and monetized (for example, valuing reduced carbon emissions based on traded carbon prices).

The approach described above also assumes that societal benefit will be maximized when producers and consumers maximize their own benefits. This may or may not be the case. End users, when analyzing from their own specific economic perspectives, will typically consider the price-performance parameters of a new technology such as nanotechnology when compared with other alternatives. Direct purchasing, capital and operational costs will surely be of concern. Depending on the user and application, the societal impacts of the product or process may or may not be of particular interest compared with specific factors of performance and functionality. For example, a medical device could be made smaller with increased operating life by incorporating a nano-enabled printed battery sheet; a user needing this medical device is likely to focus on those improved performance characteristics, including reliability and accuracy, and may well pay a premium for them. How this device is made and how it can be disposed of or recycled after use may or may not be of concern at the point of purchase. Similarly, for a novel nano-enabled insulating window glass, a customer will likely be interested in the cost of purchase and installation and in the savings in energy costs over multiple years compared with conventional window units. Considerations of the energy required to manufacture and recycle the new nano units again may, or may not, be influential in the adoption decision. Such spillovers are typically not in the control of the producer or consumer, and assessment of them may not be prominent in the purchasing or adoption decision. The extent to which these externalities are considered by individual purchasers in the valuations they make of the relative advantages or disadvantages of green nanotechnologies will vary, although they may be influenced by the availability of information, regulatory provisions, standards, and the adoption of codes of practice related to sustainability.

However, from a broader economic and societal perspective, as well as from the view of responsible and sustainable innovation, these life cycle considerations are of fundamental importance in considering the potential and applications of green nanotechnologies. Life cycle assessment (LCA) considers a "product's full life cycle: from the extraction of resources, through production, use, and recycling, up to the disposal of remaining waste" ([60], p. iv). There are a variety of approaches and tools within the rubric of LCA, including methods focusing on economic inputs and outputs and associated environmental impacts and on direct and indirect energy requirements over the life of a product (for reviews of LCA, see: [61, 62]). An LCA perspective raises a series of important issues for the evaluation of green nanotechnologies:

- While green nanotechnology applications may save energy costs and reduce carbon emissions in use, significant amounts of energy can be involved in the upstream production of component nanomaterials. Early estimates of the amount of energy required to produce single-walled carbon nanotubes (SWCNT) were relatively high [63]; another study concludes that two of the most economically viable methods of carbon nanotube production were energy intensive (due to the high temperatures and pressures required) and would thus add significant carbon dioxide emissions [64]. More recent estimates [65] continue to suggest wide disparities in energy requirements for SWNT manufacture, depending on the method used although large variations are reported for what seem to be similar processes. Using a prospective LCA approach, Wender and Seager [66] argue that the intensive energy requirements for the large-scale manufacture of SWCNT-enabled lithium-ion batteries currently make them impracticable. Energy and manufacturing costs for nanomaterial production are likely to reduce over time as process technologies are improved and new materials emerge. Nonetheless, it remains important to track and consider energy and other resource extraction costs associated with the production of materials used in green nanotechnology applications.

- Some green nanotechnology applications have raised concerns about environmental, health and safety (EHS) implications. There has been attention to potential exposure risks to workers in laboratories and factories involved in the development and manufacturing of various forms of nanostructures [67, 68]. Reviews of standards and guidance to minimize occupational and other exposure risks from nanostructures indicate a range of actions and activities under way (mainly in developed countries and by international bodies) but also limited and inconsistent evidence on longer-term implications [69]. Concerns are also extended to potential EHS risks through the use and disposal of nanostructures employed in green nanotechnology applications. For example, nanomaterials such as nZVI (nano metallic iron) are effective in absorbing and remove groundwater pollutants [70, 71]. nZVI has been used in a series of remediation projects in the USA and in several European countries including Germany, Italy, and the Czech Republic [72]. Yet apprehension has been raised about potential EHS impacts, including the toxicity of partially remediated compounds and downstream entry into water sources and plant and food chains [72–74]. Similarly, quantum dots—extremely small particles of semiconductor materials with customizable electrical and optical features—have potential green applications in low energy lighting and more efficient solar cells. Quantum dots are often comprised from cadmium and selenium and they may, under certain conditions, release toxic compounds in use or on disposal [75, 76]. There are many permutations and varied applications of quantum dots and the toxicology is not yet definitive. Additionally, at least one company (UK-based Nanoco) now offers cadmium-free quantum dots, now under development for LED lighting [77]. These examples highlight the uncertainties, particularly over the long run, associated with the EHS profiles of an unknown number of green nanotechnology applications. Risk concerns may or may not be justified, and more biocompatible alternatives may be found. Many recent and current nanotechnology EHS studies contain calls for further research and monitoring. Studies in the insurance industry have suggested that, potentially, there may be major economic consequences related to the production and use of nanotechnology [78, 79].

- Nanotechnology development and production is geographically widespread, with more than 60 countries pursuing national nanotechnology research and innovation programs [58], with the use and application of nanotechnology occurring globally. Regulation and oversight is primarily national, with some growth in nanotechnology information exchange, harmonization, and standards setting at supranational and international levels [69], including activity by the OECD through its Working Parties on Nanotechnology [80] and on Manufactured Nanomaterials [81]. Arguably, some best practices are emerging [82], but there remain significant differences by countries in the governance and regulation of nanotechnology. There are variations in the overall approaches to, and investment in, the assessment of environmental, health, safety, ethical, legal, and societal implications of nanotechnology; differences in legislative and regulatory actions, including the role of formal requirements and voluntary codes; and contrasts in the infrastructures of governance, including the roles of agencies, industry, consumer groups, think tanks, and other organizations in deliberations on nanotechnology research, commercialization, labeling, education, and regulation [83]. There are also significant differences between and among developed and developing countries in their activities and capabilities in nanotechnology and in its regulation and governance (see, for example, [84]). As global production and consumption chains emerge in nanotechnology, including green nanotechnology applications, there are anticipated opportunities for developing countries to benefit from applications pioneered in other countries. Yet there is also the potential for an inequitable distribution of risks and benefits. Intellectual property rights (including patents) in nanotechnology are assigned mainly to developed countries and a few emerging economies, potentially limiting access or increasing application costs in developing countries. Some green nanotechnology applications, for example in selectively enhancing agricultural productivity, may negatively affect countries that rely on conventional methods [85]. Nanotechnology applications may be marketed in, and nanomaterials production outsourced to, countries with less-developed capabilities for risk monitoring and regulatory control. Over the life cycle of nanotechnology products, costs and benefits may thus accrue asymmetrically.

The potential risks of new green nanotechnologies need to be compared against those of current technologies (which may also be energy intensive and present various risks) and against the human and environmental costs of not effectively addressing key global challenges (such as reducing carbon emissions or providing potable water). Yet it is apparent that labeling or promoting a nanotechnology as green does not, in and of itself, mean that this technology or its applications are sustainable or risk-free. Nor does it mean that the technology is without possible economic costs as well as economic benefits. This reinforces the point that, in considering indicators of the impact of green nanotechnology, it is appropriate to ask how that indicator contributes to the appreciation of the range of potential economic, environmental, and societal implications over time and space.

Ideally, from a broader societal perspective, LCA needs to be situated in the context of an anticipatory and socially responsible approach to governing innovation.

Anticipatory governance is the capacity to model, deliberate upon, and prepare for future developments with the involvement of key stakeholders and public engagement [86]. The methods of anticipatory governance can include foresight, scenarios, technology assessment, and other analytical techniques (such as LCA) as well as connecting research and innovation agendas and integrating the natural and social sciences. A socially responsible approach to innovation (also known as responsible research and innovation) considers social and environmental benefits in the design of research and innovation, engages societal groups, takes account of social, ethical, and environmental impacts, and incorporates openness and transparency [87].

15.6 Concluding Remarks

Landmark studies of the long-term economic impacts of major technological accomplishments are typically retrospective in nature. Martin and Tang [88] offered a review of multiple studies that have examined the consequences of public R&D investments. These studies fall into three groups: econometric studies, surveys, and case studies. Martin and Tang also note the variety of channels through which economic and societal impacts are generated, including through growth in the stock of knowledge, human capital enhancement, new instruments and methods, networks and social interaction, problem solving, new firms, and social knowledge.

A key point about such studies is that they are retrospective. The innovations are known, and a sufficient time has elapsed since their introduction for them to be recognized and for their economic and societal impacts to be assessed. Such studies are always difficult to do well, but there are methods and sources that can be tapped. When we seek to prospectively assess and measure the impacts of new technologies, there are available methods including technological foresight and forecasting methods. However, particularly if we seek to go out many years, a great deal of uncertainty is inevitable not only in the trajectory of technological development but also in predicting economic and societal conditions which will influence take-up and use. In the nanotechnology domain, prospective economic assessment is further complicated by uncertainty about the environmental, health and safety implications of some nanotechnologies.

That said, the complications and uncertainties of predicting future technology trajectories should motivate rather than discourage efforts to evaluate the likely economic implications of green nanotechnology. There are a range of methodological options that are available to probe these potential implications including the use of multi-criteria and dynamic assessment techniques, anticipatory life-cycle approaches, and scenarios and modeling. Interdisciplinary opportunities (engaging natural and social scientists) to advance these and other methodologies should be pursued.

Although development and diffusion may take longer than previously anticipated, green nanotechnologies have the potential to make significant contributions both to addressing green challenges and to fostering sustainable economic development. There appears to be substantial promise particularly in nano-enabled applications in solar cells, photovoltaics, batteries, fuel catalysts, and water filtration.

Other nano-enabled applications have the potential to reduce operational energy needs through offering comparable or better performance yet with less weight, more durability or greater efficiency. Yet attention has to be given over the life cycle to the energy and resource requirements to initially produce nano-scale materials, to the sources of energy (renewable or nonrenewable) required for their large-scale manufacture, to the fate and disposition of nanomaterials during and after use and associated environmental, health, safety and societal implications, and to broader societal values and considerations. We have suggested that such considerations can be incorporated through an anticipatory approach which models, deliberates upon, and prepares for future developments. An anticipatory approach is likely to be facilitated through a mix of measures and methods, with the ability to model and probe different scenarios and to prompt "what if" and "what about" questions.

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