PERSPECTIVES IN NANOTECHNOLOGY

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David J. Hess and Anna Lamprou

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2.1 Introduction

The advent of nanotechnology as the "next Industrial Revolution" might cause anyone with some knowledge of the environmental and health effects of previous industrial revolutions to ask some justifiably tough, skeptical questions. The promises of previous technological revolutions—a car in every garage, the peaceful atom, and better living through chemistry—have ended up generating significant environmental and health-related side effects and risks. The outcomes, in retrospect, are such that present generations would have benefited if previous generations had been more perspicacious about the regulation, design, and release of new technologies. Although precaution may be the lesson from the past, and the benefits of new technologies are often overhyped, new technologies generally involve both advantages and disadvantages, and consequently there may be little support for a political decision not to pursue at least some design variants of a proposed new technology. In this sense, nanotechnology is no different from previous generations of technologies that posed issues of both substantial societal benefit and environmental and health hazards and risks.

With respect to environmental benefits, there are various ways in which nanotechnology can contribute to products that increase energy efficiency, improve energy storage, or enable renewable energy technologies. For example, nanotechnology can contribute to the greening of the economy via applications in fuel cells, batteries, and solar photovoltaics. The combination of solar energy and hydrogen-powered fuel cells represents one way to address the challenges of intermittency associated with solar energy. Nanomaterials can also be used in electrolysis to produce hydrogen, and they generally exhibit better electronic transfer properties than bulk substances. By controlling the architecture of nanostructures, the energy conversion may become more efficient and less costly (Grätzel 1991; Wei and Zunger 1990). Nanomaterials can also play an important role in the development of methanol, which can power fuel cells. Through carbon capture and chemical conversion enabled by nanomaterials, carbon dioxide from the atmosphere or from industrial emissions can be turned into useful products like methanol, which can lower the carbon footprint of industrial processes.

More broadly in the area of energy generation and storage, nanotechnologies might prove important in improving efficiency. With respect to rechargeable batteries and capacitors, nanotechnologies are able to hold more lithium to enable batteries to have a higher charge density. Because of these energy applications, nanotechnologies could make electric vehicles more cost competitive. Nanomaterials have also been proven valuable in increasing the energy efficiency of fuel additives and insulation. They can also be used to improve fuel efficiency as catalysts, more specifically in reducing the use of platinum-group metals or even replacing them completely in surface coating and lubricants. Nanotechnology can produce very light materials, which makes transportation more efficient (Weizsäcker, Lovins, and Lovins 1998).

The use of nanotechnology to harness solar energy (nanosolar) is one example of the potential environmental benefits of nanotechnology. The advent of nanosolar could reduce the cost of solar energy significantly and rapidly, and consequently the potential environmental benefits of this type of nanotechnology are very attractive. However, the lack of information about the health-related and environmental side effects of ubiquitous nanotechnology, even nanosolar, suggests a much more unsettling picture. Using the case of solar energy as an example, in this chapter we explore how environmental social theory could be developed to shed light on complex policy issues regarding the evaluation and regulation of new technologies. We first explore the potential environmental benefits and hazards of nanosolar, followed by a consideration of the differences in strategies used to encourage more precautionary regulation.

2.2 Theoretical Background

In an ecological sense, most scientists now recognize that the impact of human civilizations on the global environment is unsustainable. In other words, levels of human resource consumption and waste have already exceeded the capacity of the global ecosystem to replenish and process them (Daly 1990, 1996). Unless rapid changes occur in global levels of consumption and waste, the human–ecosystem relationship will collapse (Meadows, Randers, and Meadows 2004). We cannot predict exactly when the collapse will occur, but it probably will not take the form of a single, dramatic event after which civilization descends into a dark age of rampant violence and ubiquitous political chaos (Costanza, Graumlich, and Steffen 2007). Rather, collapse will be unevenly distributed across countries, continents, ecosystems, classes, age groups, and genders. Women, children, the poor, and the elderly in the coastal areas of the poorest countries of Asia, Africa, the Pacific, and the Caribbean are most likely to suffer the worst effects of collapse. In many ways, we are already seeing the emergent signs of collapse in the rampant poverty of shantytowns, the effects of increased severe weather events on coastal populations, and other global problems and disasters.

To the general diagnosis and prognosis offered by scientists, environmental sociologists have added a political economy perspective that reframes the sustainability problem as driven by a more complex set of societal factors than the biological facts of ongoing human population growth and increasing resource consumption and pollution. The treadmill of production theory (Gould, Pellow, and Schnaiberg 2008; Schnaiberg 1980; Schnaiberg and Gould 1994) and related theories of the political economy of accumulation (Foster 2005) draw attention to the tendency for most human societies, and especially capitalist societies, to accumulate wealth and to concentrate it in the hands of elites. Profits garnered by capitalist firms tend to be reinvested in more capital-intensive production processes. This investment pattern leads to higher levels of productivity and, if those gains are passed on in the form of wages, to higher consumption for workers who remain employed in the capital-intensive industries. For workers who lose their jobs due to new efficiencies in production, the government must ensure new employment and therefore must facilitate overall job creation, a goal that generally requires policies that support economic growth. As a result, even in the absence of population growth, there is a tendency for the reinvestment of profits into innovation to lead to economic growth. In turn, economic growth is historically associated with a higher level of aggregate production and consumption, which results in the growth of environmental "deposits" of wastes and pollution into the global ecosystem and "withdrawals" of resources from the system. Eventually the ecological growth in deposits and withdrawals hits the wall of ecological limits, and the specter of various collapse scenarios emerges.

There is a way out of the dilemma. Ecological economist Herman Daly (1996) calls it a steady-state economy, in which economic growth is both limited and disentangled from environmental destruction. However, the dematerialization of the economy would require significant shifts of investment into new technologies to enable the rapid greening of a variety of industries and, to date, the shifts have not occurred. Understanding the absence of a concerted, rapid, and effective policy response by the leaders of the world's industries and governments is the second major contribution of environmental social theory to the broader, interdisciplinary discussion of the environmental crises. In an ideal world, the research of natural and social scientists about impending ecological crises and their economic foundations would be taken up immediately by elected political officials and their appointees, who would respond dramatically and swiftly with new legislation and regulations to head off future collapse.

Three basic conditions result in a huge gap between the ideal response to the environmental crisis and the actual response of policymakers. First, there is no firewall between the political field and the economic field, and consequently economic elites tend to dominate the policymaking process on issues that affect their interests. Those interests include the protection of "treadmill" industries, especially industries involved in the production and use of fossil fuels and chemicals, which benefit from political inaction on environmental policy. Second, even in the absence of treadmill industries, ongoing geopolitical rivalry among nation-states involving the ultimate sanction of warfare drives national governments toward competitive growth, because countries that occupy or aspire to positions of hegemony in the global political order require growth in order to maintain the budgets that underlie support for the military, foreign aid, and a strong economic position in general. As long as other countries are growing economically, the arms race and foreign aid race are linked to competition to attain economic growth. Third, even in the absence of the first two conditions, as long as populations are growing, national governments must maintain economic growth in order to maintain the standard of living. This third factor may be the least important of the three for a variety of reasons, including the predicted leveling off of population growth by the middle of the twenty-first century, the concentration of environmental impact in countries with lower population growth, and the capacity for economies to absorb the ecological impact of population growth through economic redistribution. Nevertheless, it remains a factor, and the concentration of population growth in the urban shantytowns of the less-wealthy countries will play a significant role in the global pattern of confronting ecological limits.

Together, the three factors result in an ongoing growth logic that is built into national economies and polities. The metaphor of treadmills in environmental sociology—of production (Gould, Pellow, and Schnaiberg 2008), accumulation (Foster 2005), consumption (Bell 2006), and, we would add, weaponry—can be generally interpreted as representing an attempt to capture two historical processes: high levels of economic growth and a lack of systemic response to changes in adaptation to the global ecology. In other words, the economic and political fields support ongoing economic and ecological growth and lack the capacity to address the ecological crises generated by the growth. However, the metaphor of a treadmill is imperfect because it does not capture the overall growth logic of the economic system

with respect to the global ecosystem (see also Foster 2005). To do so, one might be better off thinking of it as an expanding treadmill in a cage: the treadmill is itself expanding, and eventually it reaches the walls of the cage of ecological limits, when the treadmill breaks down or collapses.

The metaphor of a treadmill helps capture a fundamental problem in the linkage between the economy and the global ecosystem, but it does not completely capture the dynamics of how elites respond to awareness of ecological limits. The economy is also undergoing the greening of industrial production, and the polity is undergoing a transformation of governance processes that involves the construction of a wide range of environmental regulations and reforms. The changes have been amply described in the literature in environmental sociology on ecological modernization (Mol 1995; Mol and Spaargaren 2000, 2005; Scheinberg 2003). The literature can be interpreted to claim that a new industrial revolution is taking place along ecological lines, and this interpretation ends up forcing a choice between a treadmill perspective and an ecological modernization perspective (Gould, Pellow, and Schnaiberg 2008). However, the two perspectives can be made compatible if the ecological modernization thesis is interpreted as recognition that a greening process is occurring and governance processes are changing, but the extent of such changes is highly variable across industries and countries. If interpreted in this restrictive manner, one can then recognize the coexistence of the greening of industry and governance and ongoing growth in withdrawals and deposits into the global ecosystem. Furthermore, a global perspective on sustainability, in Daly's sense, makes it possible to see that the greening of one industry and country may be associated with the export of pollution, waste, and browner industrial processes to other countries (Pellow, Schnaiberg, and Weinberg 2000; York and Rosa 2003). To date, the greening of industry and the changes in governance at a global scale have not yet addressed the fundamental issue of achieving a steady-state economy. In order for the greening of industry to be ecologically significant from the perspective of a Daly-type definition of global ecosystem sustainability, technological innovation at a global scale would have to outpace levels of absolute global growth of environmental withdrawals and sinks. To date the dematerialization of the economy generated by green technological innovation has been swamped by the overall growth of environmental sinks and withdrawals (Gould, Pellow, and Schnaiberg 2008).

Treadmill and other accumulation theories suggest a dismal diagnosis and poor prognosis regarding the capacity of technological innovation to bring about a dematerialization of the economy, and they have not offered much in the way of a therapy. Part of the appeal of ecological modernization theory is that it has analyzed policy strategies for developing cooperative relations among the state, industry, and civil society in order to move forward on pressing problems of environmental degradation. In contrast, to the extent that there is any treatment program in accumulation theories, it tends to draw attention to the role of social movements, including blue-green coalitions of labor and environmental groups, in providing the basis for a less-cooperative and more conflict-oriented strategy that contests the power of elites who have ignored warnings about environmental crisis (Gould, Pellow, and Schnaiberg 2008). Here, we suggest, is the starting point for a more interesting and fruitful debate, recast in somewhat different terms, that might move forward the field of environmental sociology as a whole. Which strategy poses a better way out of the dilemma of the treadmill: building complex partnerships among civil society organizations, the state, and industry; the confrontation, protest-oriented repertoires of the social movement sector of civil society; or some combination of both?

To be clear about the argument, from a diagnostic and prognostic perspective, the differences between a treadmill of production theory and an ecological modernization theory can be resolved. There is little doubt that greening processes and governance changes are occurring (ecological modernization), but the changes have not occurred at a sufficient pace to compensate for growth in global levels of environmental sinks and withdrawals, which are driven by the capitalist accumulation process in addition to interstate competition and, to a lesser extent, population growth (treadmill of production). If current trajectories continue, then scenarios of uneven collapse will become increasingly evident. However, the closure of the theoretical controversy on one front might also serve as a starting point for questioning the analytical focus of the field of environmental sociology on diagnosis and prognosis. In other words, recognition of closure of the debate might provide an occasion for exploring the potential of the field to contribute to the analysis of strategies of environmental policy. By linking environmental social theory to environmental policy, the field is challenged to bring its theoretical insights and empirical research findings into contact with real-world problems of pressing policy significance. In this chapter we use the case of the convergence of solar energy and nanotechnology not only as an exemplar of the complex mix of benefits and risks that nanotechnology poses but also as an opportunity to develop an analysis of how environmental social theory and environmental policy might be brought together.

2.3 Nanotechnology and Solar Energy

The "next Industrial Revolution" is full of promises and hype about how nanotechnology will change every aspect of human existence. The claims are at times alluring but also foreboding: Drug delivery and diagnostics will be transformed, new materials will become available at a much lower cost and higher strength, potable water will become readily available through new processes of desalinization, new systems of surveillance and chemical monitoring will become possible, and a new generation of armaments and weaponry will emerge. The promises also extend to environmental amelioration, an issue that makes an environmental sociology of nanotechnology a complicated enterprise: Nanoscale chemicals may become available to replace the current generation of toxic, chlorinated chemicals; nanomaterials could lead to breakthroughs in the use of fuel cells and batteries; new materials based on nanotechnology could reduce the impact of mining for metals; and nanoscale electrical materials will be both smaller and more conductive, leading to revolutions in electrical use and efficiency and a post-silicon era for computing. Among the environmental benefits, we focus on solar energy, partly because the promise here is perhaps the most appealing: solving the problem of climate change through nanotechnology (Schmidt 2007).

Solar energy has long been the alternative energy technology preferred by social movements, partly because its modular design can be made compatible with decentralized and democratic ownership (Hayes 1979; Laird 2001; Reece 1979). Furthermore, from an energy perspective, solar energy is potentially much greater than other clean or renewable energy sources, and, to date, it has been less controversial than wind farms (Breukers and Wolsink 2007; Firestone and Kempton 2007). Solar, wind, and related renewable-energy technologies have long been recognized as the basis for an economy that enables the dematerialization of its energy consumption; hence, they are likely to be essential ingredients in a transition to a steady-state economy. However, the great problem with solar energy has been its high cost. Eventually, new materials, such as the ones that are already appearing in thin-film technology, will bring down the costs and reduce the environmental impacts of production. Grid parity, the point at which the price of solar energy becomes equivalent to that of energy supplied over the grid primarily from a fossil-fuel source, will occur sometime between 2012 and 2020. When the convergence of prices is reached, industry analysts predict that there will be an explosion of solar energy production and a rapid transition toward solar energy. This is not to say that other energy sources—such as wind, geothermal, and tidal energy—will not be important, but solar energy is different because it is a beneficiary of the rapidly advancing innovations of photonics, materials science, and other fields. Although perhaps not enjoying quite the rapid improvements associated with Moore's law, solar energy is likely to become much less expensive over time, not only in relationship to fossil fuels and nuclear energy but also in relationship to other renewable energy sources.

There are many ways that scientists are trying to achieve a revolution in solar energy technology with nanoparticles: photosynthesis through the use of titanium dioxide nanoparticles; nanoparticle encapsulation in polymers; the development of calcopyrites produced as thin film photovoltaics; the use of molecular organic solar cells; organic polymer photovoltaic systems with nanoscale layers; the addition of single-wall nanotubes to conduct polymers that improve efficiency; smaller size nitride semiconductors, which result in more efficient photovoltaic systems; and photovoltaic nanoparticles coated with thin films of polymer that can create cheap flexible solar cells. Through a combination of the many innovations that are currently in laboratories or beginning to be tested in markets, nanotechnology becomes central to the field of solar energy by offering the potential to accelerate the decline in solar energy costs and even to help solar energy become the cheapest form of energy.

Nanotechnology and clean energy consultant Bo Varga states the potential frankly and succinctly: "Solar growth at 20 percent per year for fifty years can replace fossil fuels and nuclear and remove the causes of global warming" (2007, 1). One may argue with his assumptions and projection, but the fundamental proposition is interesting as a possible way out of some very difficult energy problems posed by climate change. There is little incentive for any country to leave oil, coal, and natural gas in the ground, and the increase in global demand will only make it more difficult to resist the temptation to drill, extract, sell, and use more fossil fuels. Carbon trading agreements could make fossil fuels less competitive with respect to renewable energy technologies, but to date the schemes in Europe have proven to be less effective than originally projected (Hansen 2009). A technological development that would bring about the widespread diffusion of a much cheaper alternative could provide an even more powerful incentive for countries and firms not to continue to use fossil fuels. Solar energy could provide that technological innovation.

To its credit, the U.S. government has recognized, albeit in a limited way, the potential of the nanosolar convergence. If one looks through the research projects funded by the Solar America Initiative, a significant number of them involve nanocrystals, nanotubes, nanowires, quantum dots, and other nanoscale materials (U.S. Department of Energy 2007). By 2011, a few companies were already bringing nanosolar technologies to market. Innovations include a printable nanocrystal technology by Solexant and a nanoparticle ink printed on thin foil by Nanosolar. The new, printable technologies enable solar photovoltaics to be produced without the glass panels that are characteristic of the older-generation, silicon-based photovoltaics.

Nanosolar convergence promises to do more than simply bring down the costs of solar and make it the preferred form of energy generation. Future scenarios include a complete redesign of energy products and technologies. Just about any surface that receives light, including clothing, could provide an opportunity for energy generation. Nano-antenna arrays can produce energy based on infrared resources. A flexible, plastic-like nanosolar cell could be sprayed onto other materials much in the way that one can spray paint onto a surface today. Stefan Lovgren, *National Geographic* correspondent and winner of the American Association of Advancement of Science journalism award, describes the following scenario: "A hydrogen-powered car painted with the film could potentially convert enough energy into electricity to continually recharge the car's battery. The researchers envision that one day 'solar farms' consisting of the plastic material could be rolled across deserts to generate enough clean energy to supply the entire planet's power needs" (Lovgren 2005). Lovgren goes on to estimate that only 0.1 percent of the Earth's surface would be needed to replace all human energy needs with this "clean and renewable" alternative.

It is impossible at this time to know how much, if any, of the promises of a nanosolar future will be realized by 2050 or 2100. In this light, while nanosolar may be new and full of possibilities, the hype surrounding it is not. Such hype is similar to that which pervades other aspects of the nanotechnology revolution and that which accompanied previous "technological revolutions" such as nuclear energy during the 1950s and 1960s, which promised to provide the world with an endless supply of cheap, clean electricity. Even today, nuclear energy advocates continue to suggest that their energy source, not solar energy, promises to solve the world's energy needs and greenhouse gas emissions problems. Nor is nuclear the only energy selected by contemporary industry to make such promises. Not surprisingly, there is also considerable hype around carbon sequestration technologies as the best choice of energy futures.

Although we have used the term *hype* to describe the futures promised by advocates of various "clean" energies, their visions of a future of ubiquitous and cheap solar energy are also expressions of a struggle among actors for dominance as important players in a highly competitive energy industry and field of funding competition. One site where this conflict plays out with special intensity is energy research funding, and in the United States there have been significant differences between Republicans and Democrats on the issue. The Republican administration of President George H. W. Bush was more supportive of research on nuclear energy and fossil fuels than renewable energy, and it attempted to cut the federal government budget for solar energy research and energy-efficiency technologies (DuBois 2008). In contrast, the Democratic administration of Barack Obama steered more resources toward solar and other renewable energy resources, and made substantial cuts in research funding for nuclear energy and fossil fuels. Even so, the budget of the Obama administration for energy research and development continued to provide higher support for nuclear energy ($495 million) and fossil fuels research ($438 million) in comparison with solar ($302 million), wind ($123 million), and geothermal energy ($55 million) (U.S. Department of Energy 2010).

2.4 Nanosolar Risk and Uncertainty

In addition to the parallel between the hype surrounding nuclear energy during the 1950s and the hype around nanotechnology and nanosolar today, one might draw a second parallel between the two energy sources, one that cuts deeply into the rosy futures described above. It took decades for the effects of uranium mining on local environments, the health effects of radiation exposure, the possible nightmare of terrorist attacks on nuclear energy plants, the risks of severe events such as the earthquake and tsunami that affected the Fukushima reactors, and the problem of waste disposal of spent nuclear fuel to become recognized as a bundle of negative side effects generated by nuclear technology. In a similar way, research is slowly emerging on the environmental, health, and safety (EHS) implications of nanotechnology (for reviews, see Donaldson et al. 2006; Helland et al. 2007; Lam et al. 2006; Singh and Nalwa 2007). Nongovernmental organizations such as Environmental Defense, the ETC Group, Friends of the Earth, and Greenpeace have sent warning signals about the potential for nanotechnology to repeat the mistakes of the past (Hess 2010; Lamprou 2010). Whether one makes the comparison with nuclear radiation or previous generations of materials that proved hazardous (such as asbestos and chlorinated chemicals), emerging knowledge on the EHS implications of nanotechnology suggests that society may be in the process of repeating its past mistakes by unleashing a new generation of toxic materials into the environment.

Although many of the world's industrialized powers provide some government funding for research on EHS implications of nanotechnology, several of the leading civil-society organizations in the United States, as well as prominent researchers and policymakers, have argued that the research has been systematically underfunded, whereas government support for the commercialization of nanotechnology has been much more forthcoming (Hess 2010). As a result, more is understood about the potential benefits of nanotechnology than about the risks, dangers, and unwelcome surprises.

Engineered nanoparticles are already entering the biosphere through waste streams and airborne particles. A main source of environmental exposure to engineered nanomaterials is in the waste streams from factories and research laboratories. Studies point toward the possible effects of nanoparticles on microorganisms as well as small animals such as earthworms (Brumfiel 2003; Oberdörster 2004). Studies conducted at Rice University have shown that nanoparticles could easily be absorbed by earthworms; this research suggests that it is possible for nanomaterials to move up through the food chain and reach humans (Brumfiel 2003). Another source of environmental exposure is the release of airborne nanomaterials from powders, which present especially high levels of concern because they can easily enter the human body through inhalation and become deposited in the lungs (Maynard and Kuempel 2005; Oberdörster 2000, 2004; Oberdörster et al. 2004; Oberdörster, Oberdörster, and Oberdörster 2005). Studies have shown that inhaled particles, in general—even when they have a low intrinsic toxicity to cells—may cause diseases of the lungs if the dose is of a particular strength. Diseases may arise because the immunological defenses of the lungs become overloaded if the total surface area of the affected lungs is large enough (Faux et al. 2003).

In particular, research on the toxicity of nanomaterials has characterized some risks and uncertainties associated with three commonly used nanoparticles: titanium dioxide, fullerenes (C_{60}), and carbon nanotubes.[1] In the case of nano-sized titanium dioxide, toxicity research shows that when they interact with cells after inhalation the nanoparticles exhibit more toxic properties than in their bulk form (Donaldson et al. 2006; Heinrich et al. 1989). In the case of fullerenes, research based on computer modeling has indicated that C_{60} molecules may bind to and deform nucleotides when they come into contact with each other (Zhao, Striolo, and Cummings 2005). Recent studies have also implicated fullerenes in oxidative stress in the brains of largemouth bass and have suggested other adverse physiologic impacts on aquatic organisms (Hood 2004; Oberdörster 2004; Zhu, Oberdörster, and Haasch 2006). To date the research does not give a clear answer about how nano-C_{60} behaves in aquatic environments, and until more is known about the toxicity, compounds containing nano-C_{60} must be handled carefully (Lyon et al. 2005).

When it comes to carbon nanotubes, there is evidence to suggest that they may stimulate mesenchymal cell growth and cause granuloma formation and fibrogenesis (Donaldson et al. 2006). Carbon nanotubes can also be much more toxic than carbon black and quartz, and they represent a serious occupational health hazard, especially in chronic inhalation exposures (Dreher 2004; Lam et al. 2004).[2] Tests on single-wall carbon nanotubes (SWCNTs) in rats and mice showed toxicity in the form of granuloma and inflammation (Lam et al. 2004; Warheit et al. 2004). Other studies, also conducted with mice, measured the pulmonary responses to SWCNTs delivered by pharyngeal aspiration and suggested that if workers are exposed to such particles at the current permissible exposure limit, they may be at risk of developing lung lesions. The rapid fibrogenic response to aspiration of SWCNTs indicates the need for more extensive inhalation research (Shvedova et al. 2005; see also Poland et al. 2008).

The most important finding from research, with respect to the hazards of nanoparticles, remains the fact that cells and organs may have toxic responses even to normally nontoxic substances when they are exposed at a sufficient dose at the nanoscale (Borm and Kreyling 2004; Renwick, Donaldson, and Clouter 2001). Ultimately, the capacity for the kidneys to separate and discharge chemicals depends on their solubility and surface coating (Borm and Kreyling 2004). However, some particles selectively deposit in particular organs or cells, and there is a possibility that nanoparticles can penetrate cells or cross biological barriers such as the blood–brain barrier (Illum and Davis 1987). Particles smaller than one hundred nanometers (100 nm) in diameter are not only able to enter the lung interstitium and become deposited in the lungs but can also enter the bloodstream (Ferin and Oberdörster 1992; Maynard 2006; Oberdörster et al. 2002), and they can enter the liver and brain through the nerve axons (Oberdörster 2000; Oberdörster et al. 2002, 2004).

In summary, nanomaterials pose some documented risks and many unknown dangers to human health, nonhuman organisms, and the environment. Although exposure does not automatically translate into disease, the preliminary and underfunded research on the EHS dimensions of nanomaterials for humans and other animals suggests the need for a precautionary approach to the regulation of nanomaterial release into the environment. But regulatory policy should also recognize that some types of nanomaterials are likely to be more dangerous than others. It may be possible that some designs of nanotechnology materials will turn out to be relatively more dangerous, in terms of human health risk, and relatively amenable to disposal that minimizes diffusion into the environment. For example, cosmetics and other personal care products that use free nanoparticles in creams that are applied directly to the skin are more likely to pose higher levels of risk due to increased contact with human bodies and a greater likelihood that the materials will degrade outside of a safe disposal process. However, even in that case we still do not know the levels of risk involved (Berube 2008). In general, free or unembedded nanomaterials are more dangerous than those that are embedded in a matrix structure or grown in a substrate. Assuming that most nanosolar products could be embedded in a matrix structure at a molecular level and placed in sealed solar panels at a product level (an assumption that may eliminate the spray-on nanosolar materials described above), this particular design of nanosolar materials may present relatively low levels of hazard and risk compared with other nanotechnological products. In other words, from a toxicological perspective, printed nanosolar on thin films may be a safe option if the materials do not degrade during use and can be recycled in a safe way. The alternate prospect of a transparent nanospray that can turn windows into photovoltaic generators may present exposure problems to both workers who use the spray and users who are exposed to the degradation of the materials due to sunlight, rain, wind, and other weather factors.

At this point, we know little about which particular kinds of nanotechnology designs can be deemed safest. The public, policymakers, and NGOs are faced with a situation of "undone science," or inadequate levels of research to provide a basis for a public-interest perspective on policy action on the risks of nanotechnology (Frickel et al. 2010). As in the case of funding for solar energy research, the budgets for EHS research on nanotechnologies have done relatively poorly during Republican administrations and only relatively better under Democratic administrations. For example, the funding level for EHS research increased from about $35 million in 2005 during the Bush administration to $117 million in 2011, during the Obama administration (Erickson 2011). The growth in the funding for nanotechnology research and product development requires a constantly increasing level of EHS research in order to keep pace, and not all funding is directly relevant to understanding human health and safety issues.

In the United States, hundreds of nanotechnology products had been released into markets by 2011, but the Environmental Protection Agency had only managed, after several years of delay, to put in place a voluntary regulatory program. The agency added to the existing and weak voluntary program an interpretation of the Toxic Substances Control Act that required

a premanufacturing notice of nanoscale materials only if they were structurally different from larger chemicals that were already on the market. The classification decision is highly controversial, because nanoscale materials that are structurally similar to preexisting chemicals may have significantly different biological properties due to their size, as noted above.

In summary, the phenomenon of nanosolar presents two underlying conflicts or tensions. First, there is widespread governmental and industrial interest in nanotechnology, but solar energy has received relatively low levels of support due to competition from fossil fuels and nuclear energy. Consequently, nanosolar has not been brought to the forefront of the nanotechnology revolution. The attention it receives in the future, therefore, depends largely on a purely rationalistic assessment: how the potential for nanosolar to bring down the cost of solar energy is assessed, as well as how the importance of the rapid commercialization of renewable energy technologies is prioritized. Second, nanosolar could reduce environmental side effects resulting from human consumption by making manufacturing and electricity generation much more efficient and cost effective, although it could also generate new environmental side effects through EHS hazards and risks. Assuming that nanosolar materials are embedded in matrices or grown in a substrate, those hazards and risks would likely be concentrated in the workplace where the materials are produced and in disposal sites where sealed panels may break, matrices may degrade, and materials embedded in matrices may be released into the environment. Potentially, those problems could be addressed by extending existing models for handling toxic waste.

Given this situation, a complex response to nanosolar is in order. One would want to see much more research funding, both for the technology itself and for the EHS risks associated with different types of nanosolar design. By setting research funding goals that would allow the two strands of research to converge, it would be possible to know something about what kinds of nanosolar designs are most likely to pose minimal EHS risks to best protect workers, users, and the environment from EHS hazards posed by the new technologies.

2.5 Policy Strategies and Nanotechnology

Treadmill of production theorists and other accumulation theorists in environmental sociology would have no trouble explaining the rush to commercialization of nanotechnology, the government support of nanotechnology research, the relatively low levels of both solar energy research and EHS nanotechnology research, and the failure to generate a new regulatory framework for nanotechnology. Industrial interests, especially those of the fossil fuel and chemical industries, have dominated the policymaking processes that shape the destiny of nanosolar. Scientific research groups and civil society organizations are struggling to stay abreast of the problems generated by the premature release of new substances into the environment after significant investment and commercialization had already taken place. From the perspective of environmental social theory, there is little of interest in the EHS risks generated by the nanotechnology revolution. It is yet another case of capital seeking new investment opportunities and attempting to block or slow any regulatory impediments that might reduce access to those opportunities.

Although the case of nanotechnology may pose little theoretical interest for accumulation theories other than more grist for their mills, we suggest that the challenge of making sound nanotechnology policy, including nanosolar policy, does pose a greater opportunity for environmental sociology. If one begins with the assumption that a policy goal of developing a safe and responsible nanosolar industry offers potentially high societal and environmental benefits, then another analytical vista is opened up: the study of policy strategies and their effectiveness.

Those who assume that a more robust regulatory policy and higher level of EHS research would be generally beneficial would be advocating a shift in policy toward a less market-oriented and more state-interventionist approach to industrial regulation. One can then distinguish two strategies for increasing the likelihood of implementing this policy approach: an "activist" approach, modeled on historical social movements with their extra-institutional repertoires of action, such as street-based protest and civil disobedience, and an "advocate" approach, involving institutional repertoires of action that are associated with reform movements, such as working within the political field via elections, petitions, and lobbying (Hess 2007). Unfortunately, there is no good, concrete example of these two ideal types in the field of nanotechnology activism and advocacy. However, we now briefly examine the work of two organizations—the ETC Group and Environmental Defense—that have attempted to approximate the two strategies, before returning to the related theoretical implications for environmental sociology (see also Hess 2010).

The ETC Group has called for a complete moratorium on all laboratory research and commercial applications of nanotechnology until an "International Convention on the Evaluation of New Technologies" is established (ETC Group 2003a, 2003b). With respect to nanotechnology policy, the group has not engaged in extra-institutional repertoires of action characteristic of social movements, but it has built bridges with labor, consumer, and human rights groups. The primary policy tactic to date has been the circulation of petitions, publication of reports, and participation in the World Social Forum. Until now, ETC's petitions and public information campaigns have not had much policy impact. Industry has rejected the group's call for a complete moratorium until a global regulatory structure is in place, and so far the public has not taken up the NGO's warnings about the potential risks of nanotechnology. Although nanotechnology is still in a less-mature phase than biotechnology was in the late 1990s, a repeat of the public rejection of genetically modified food, especially as it occurred in Europe, has yet to happen for nanotechnology. The special place of food in cultural politics and its status as a product that is ingested on a daily basis made it easier and more tangible for social movement organizations to politicize genetically modified food. However, the story for nanotechnology is far from over, and it is possible that an anti-nanotechnology movement equivalent of that for genetically modified food could emerge (on the parallels with genetically modified food, see Sandler and Kay 2006; cf. Thompson 2008).

In contrast, Environmental Defense developed a partnership arrangement with DuPont to articulate a best-practices framework for voluntary participation by industry, and the organization helped the Environmental Protection Agency develop a voluntary program of chemical registration (Environmental Defense–DuPont Nano Partnership 2007). Over time, Environmental Defense advocates became frustrated with the voluntary approach and increasingly called for a definition of all nanomaterials as "new chemicals" under the Toxic Substance Control Act (Denison 2007c). Environmental Defense also called for a higher budget for EHS research, a separation of the nanodevelopment budget from the EHS budget, and other regulatory changes for the United States (Denison 2007a, 2007b).

From the perspective of environmental social theory, the contrasting policy approaches of the ETC Group and Environmental Defense represent relatively minor disagreements within an overall policy strategy of a shift toward higher levels of regulation of nanotechnology. However, the differences in the relative impact of the two strategies are potentially of interest for answering the kinds of questions that an environmental sociology or environmental policy might ask. In this particular case, a conflictual strategy of a call for a complete moratorium and social movement mobilization has had little impact on policy. More generally, the conflictual strategy may be an effective policy strategy for some political issues. As we have shown elsewhere in a comparative analysis of industrial opposition movements, the results often lead to partial success in the form of a partial moratorium (Hess 2007). In the case of nanotechnology, in particular, we are most likely to see partial moratoria emerging for specific particle types found in consumer products, such as nanosilver in clothing and nanoparticles in sunscreens and cosmetics. In contrast, a cooperative strategy that has involved partnerships among industry, the government, and civil society has produced some changes in the nanotechnology policy. The strategy of dialogue, partnership, and politicking through federal government institutions seems to be paying off for Environmental Defense and partner organizations, as it has showed some progress on achieving policy goals in Congress, especially relating to levels of EHS research funding.

From the perspective of treadmill theory, the work of Environmental Defense would be considered "policy tinkering." Gould and colleagues note that such approaches do have some environmental benefits and offer some potential, but they also find that such approaches do not address fundamental institutional dynamics that drive ongoing destruction of ecosystems (Gould, Pellow, and Schnaiberg 2008). Instead, they are more supportive of a social movement strategy that involves coalitions among labor, environmental, and other transnational social movement organizations. Presumably, the strategy would also maintain a focus on the fundamental goal of building a steady-state economy. Of course, the two strategies do not need to be considered in a zero-sum relationship. Having both strategies work in tandem is likely to be more effective than either strategy employed on its own, particularly because of the potential for flank effects. In other words, the threat of a public uptake of a complete moratorium on nanotechnology posed by the ETC Group may help open up political opportunities for Environmental Defense and other insider organizations that are attempting to institute industry-wide best-practice standards and achieve incremental regulatory and research funding reforms. Likewise, the process of educating legislators that Environmental Defense has undertaken may open up political opportunities for partial moratoria.

2.6 Conclusion

The treadmill tendency for capital to invest in new technologies that increase the efficiencies of production, as well as the tendency for governments to invest in new technologies with military and economic potential, will lead to ongoing nanotechnology innovations. Those innovations could result in the growth of nanosolar, which in turn could generate new levels of toxic exposure to workers, consumers, and the broader environment. One might argue that the rush to nanotechnology, especially outside the framework of a robust EHS research agenda and extensive regulatory oversight, is merely one more example of accumulated capital being channeled into a new industry that will generate higher profits and better weapons at the expense of a new level of environmental destruction. In a worst case scenario, ubiquitous, spray-on, plasticized solar panels will generate new energy sources along with growing levels of toxic chemical exposure.

On the other hand, from an ecological modernization theory perspective, one might counterargue that the development of nanosolar will provide a new, inexpensive source of energy that could substantially displace other, less environmentally desirable alternatives, such as nuclear energy and carbon sequestration for coal. Furthermore, by utilizing best practices in the design, manufacture, use, and disposal of the technology, spray-on nanosolar designs may end up being excluded from production, and safer nanosolar designs can be brought into existence in ways that are consistent with

the emerging research of the EHS field. As a result, nanosolar might actually lead to a significant dematerialization of the economy in the sense of reduced aggregate levels of human impact of greenhouse gases on the global ecosystem.

Although playing the two frameworks against each other may be helpful in elucidating the environmental politics at play in the development of nanosolar, we are not trying to use the case of nanosolar to reopen the debate between treadmill of production theory and ecological modernization theory. In our view, the debate over diagnosis was largely resolved as follows: the greening of industry and the ecological modernization of society are occurring, but the changes are highly localized and industry specific, and to date they have not fundamentally addressed the challenge of growth in aggregate withdrawals and deposits into the global ecosystem. Even if at least half of the world's energy is produced from nanosolar by the year 2050, it is very possible that it will not be enough to enable a steady-state global economy to be achieved, because overall energy consumption may continue to grow so much that nanosolar does not displace fossil fuels enough to bring down atmospheric greenhouse gas emissions. Hence, even with a nanosolar revolution, aggregate levels of absolute withdrawals and deposits from the global ecosystem might continue to rise.

Rather than use the case of nanosolar to give new life to the controversy between treadmill of production theory and ecological modernization theory, we are instead arguing that the debate be transposed into the sociology of policy. The controversy left unanswered by the debate over diagnosis and prognosis was the crucial question of treatment, of an analysis as to which strategies for political and economic change are most likely to bring about the dematerialization of society. Even if one suspects, as we do, that the prospect of solving global greenhouse gas emissions with ubiquitous nanosolar is overblown, one might nevertheless agree that, as long as governments such as that of the United States are investing over $1 billion per year in nanotechnology research, then a priority within that investment portfolio should be nanosolar technology development coupled with EHS research that would enable the determination of how to design nanosolar in ways that minimize environmental, health, and safety risks. Although one might have some qualms about the potential toxicities of nanosolar, the other, "back to the future" energy scenarios for twenty-first-century energy production appear even less appealing, such as a return to the mid-twentieth-century world of nuclear energy or the nineteenth-century world of coal, albeit cleaned up with carbon sequestration technology. Both of these energy solutions have well-known shortcomings, including the threat of terrorist attacks, meltdowns, nuclear waste disposal, ecosystem degradation from coal mining, the unproven effectiveness and availability of underground storage, the lethal toxicity of carbon bubbles, and the cost of carbon sequestration technology. Even wind energy, which is currently cost effective at a large scale, poses problems of intermittency, storage, and transmission. As a result, an energy policy that would enable the possibility of a more rapid transition to grid parity for solar energy would seem to be a reasonable part of a balanced future energy research portfolio.

To shift environmental social theory toward the analysis of environmental policy, one could argue that no incremental or reformist policy interventions will work, and that, because more radical approaches have been taken off the table of policy debate, collapse is inevitable. In that case, retreat into marginalized, ecosocialist movement activism is probably the only viable strategy. But if one assumes that some incremental changes are possible and that they will at least mitigate the worst effects of collapse, then one has shifted the debate onto the grounds of an analysis of mainstream policy. We have developed a contrast between extra-institutional activism and institutional advocacy as ideal types. To some extent the contrast between these two different strategies for reform approximates the underlying theoretical differences in environmental social theory between the treadmill of production and ecological modernization approaches. However, the connection is probably only coincidental and contingent. For example, one might agree with the fundamental treadmill argument that, to date, the greening of industry has not had a significant impact on levels of absolute global deposits and withdrawals, and yet one might still consider an incremental, institutional advocacy policy strategy similar to that of Environmental Defense as more effective in this particular historical circumstance. Conversely, one might argue that—at least in some countries and industries—the greening of industry has significantly reduced local deposits and withdrawals into the ecosystem, yet still prefer an extra-institutional activist policy strategy as the best way to move such localized and industry-specific victories forward. More to the point, it could also be argued that a mixture of the two strategies is more likely to be effective than either solely on its own. Whichever position one takes, the broader point is that any research on this issue may help open up new vistas in environmental sociology that have been inadequately conceptualized and explored in this theoretical debate. This could help shift environmental sociology from diagnosis and prognosis to treatment, which in turn could offer more effective strategies for policy reform.

To avoid misunderstanding, it should be clear that the analysis of policy and political strategy should be distinguished from prescriptive discourse. Therefore, we are not suggesting that environmental social scientists begin proselytizing with normative statements about what should be done. Instead, we are arguing for a more empirically oriented form of social science research that seeks to understand what kinds of political strategies work best given a particular set of environmental policy goals and historical circumstances. Therefore, a key question arises as to which advocacy strategies are likely to be most effective if we wish to see a greater government role in solar research, nanosolar research, EHS research, and nanotechnology regulation. We now know that the patient is sick and possibly terminal; those debates are over. What we do not know and need to know is which therapies are

most likely to help or, at a minimum, which therapies will reduce the misery as the disease of global ecosystem collapse runs its course.

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