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# THE ENVIRONMENTAL IMPLICATIONS OF AN EMERGING ENERGY TECHNOLOGY: PHOTOVOLTAIC SOLAR CELLS—A STUDY OF THE TOXIC ASPECTS

*Marko M. G. Slusarczyk\**

## I. INTRODUCTION

The chilling realization that the world fossil fuel supply is limited<sup>1</sup> and vulnerable to political and economic manipulation<sup>2</sup> has prompted the United States' frantic search for alternative energy sources. Increasingly, the sun is being looked to as an energy source of the future.<sup>3</sup> Solar energy is perceived as an inexhaustible and environmentally benign alternative.<sup>4</sup> After all, the sun's energy is free,

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1. If the present rates of usage continue, petroleum supplies can be expected to last only another 47 years. L. VOGT & D. CONNER, *ELECTRICAL ENERGY MANAGEMENT* 2 (1977).

2. The overdependence of the United States on imported oil serves as an example of the type of political and economic manipulation possible.

In 1960, the ministers of five oil exporting countries formed an alliance, the Organization of Petroleum Exporting Countries (OPEC). The alliance was virtually ineffective as a bargaining unit until 1970, when Libya successfully broke the 20-year 50/50 profit sharing arrangement with the oil companies, established the power of producer countries to raise posted prices unilaterally, and forced the oil companies to accept the principle of retroactive price increases. Spurred by Libya's success, OPEC became a significant bargaining unit. OPEC's control of oil prices was further reinforced by the shortages created by the embargo of 1973.

In 1973, the Arab oil exporting countries attempted to influence the United States foreign policy with respect to the State of Israel through an embargo on oil exports to the United States. Although the embargo failed to achieve the desired political objectives, it created severe shortages and demonstrated America's vulnerability to oil cutoffs by foreign suppliers. The effect of OPEC's new-found power can be seen in the per barrel revenues. In the period from 1950 to 1970 the revenues approximately doubled, between 1970 and 1974 they increased ninefold. F. WYANT, *THE UNITED STATES, OPEC, AND MULTINATIONAL OIL* 65-85 (1977).

3. As part of the national energy goal of the National Energy Act, Congress felt that "[f]or long-term economic growth, the United States will have to make increasing use of renewable and essentially inexhaustible energy sources as substitutes for declining fossil fuel resources. One of the major renewable resource technologies currently available is that involving solar heating and cooling." H.R. REP. NO. 496 Pt. 4, 95th Cong., 1st Sess. 17 (1977).

4. ECOSYSTEM IMPACTS RESOURCE GROUP, RISK AND IMPACT PANEL OF THE COMMITTEE ON

owned by no one, and the energy potential of the sun is vast: in 64.6 seconds the amount of solar energy reaching the earth equals the amount of electrical energy used in the entire United States during 1979.<sup>5</sup> What could be more natural and environmentally sound than the sun?<sup>6</sup>

The practical use of solar energy, however, presents a number of drawbacks. Although solar energy is there, free for the taking, to be useful it must be converted into energy of the form needed to operate industrial machines, automobiles, lightbulbs, furnaces, and other energy-consuming devices.<sup>7</sup> The equipment necessary to perform this conversion costs money and may cause environmental harm.<sup>8</sup> Thus, in reality, solar energy is not free and solar energy is not necessarily environmentally benign.

Photovoltaic solar cells<sup>9</sup> are one method of harnessing the sun's energy; they convert sunlight directly into electricity.<sup>10</sup> In order for solar cells to be a commercially viable source of energy, however, the cost of the electricity generated by solar cells must be comparable to that generated by more conventional methods, such as hydro, oil, coal, or nuclear.<sup>11</sup> Extensive economic analyses of various technological options have been undertaken.<sup>12</sup> These analyses, however, for the most part have not included the environmental effects of photo-

NUCLEAR AND ALTERNATIVE ENERGY SYSTEMS, NATIONAL RESEARCH COUNCIL, ENERGY AND THE FATE OF ECOSYSTEMS 44 (1980) (Supporting Paper 8) [hereinafter cited as ECOSYSTEM].

5. The best estimate of the energy received from the sun by the earth's atmosphere is  $3.75 \times 10^{21}$  Btu per year. J. MERRIGAN, SUNLIGHT TO ELECTRICITY—PROSPECTS FOR SOLAR ENERGY CONVERSION BY PHOTOVOLTAICS 22 (1st paperback ed. 1980). In 1979,  $2.25 \times 10^{15}$  watt-hours equaling  $7.68 \times 10^{15}$  Btu's of electricity, were used in the United States. THE WORLD ALMANAC AND BOOK OF FACTS 1981 at 184 (H. Lane, ed.). Using  $3.16 \times 10^7$  seconds per year, the annual electrical usage within the United States corresponds, therefore, to 64.6 seconds of sunlight on the earth.

6. See Daneke, *Solar Futures: A Perspective on Energy Planning*, in ENERGY AND ENVIRONMENTAL ISSUES 148 (M. Steinman ed. 1979).

7. For a general discussion of energy consumption and sources, see MERRIGAN, *supra* note 5, at 1-21.

8. A STUDY GROUP SPONSORED BY THE FORD FOUNDATION AND ADMINISTERED BY RESOURCES FOR THE FUTURE, ENERGY: THE NEXT TWENTY YEARS 502 (1979).

9. See MERRIGAN, *supra* note 5.

10. Electricity is a particularly valuable product of solar energy since it is readily converted into other forms of energy, such as heat, motion, light, or sound. Furthermore, existing power distribution grids and appliances could be used without major modification. For a further discussion, see ENERGY FUTURE—REPORT OF THE ENERGY PROJECT AT THE HARVARD BUSINESS SCHOOL 209 (R. Stobaugh & D. Yergin eds. 1979).

11. MERRIGAN, *supra* note 5, at 110.

12. For an example of an economic analysis, see 2 OFFICE OF TECHNOLOGY ASSESSMENT, U.S. CONGRESS, APPLICATION OF SOLAR TECHNOLOGY TO TODAY'S ENERGY NEEDS (1978) (U.S. Gov't Printing Office Stock No. 052-003-00608-1).

voltaics, or have dismissed them as negligible,<sup>13</sup> assuming photovoltaic solar cells to be environmentally benign.<sup>14</sup>

Since solar cells may cause some environmental harm and are likely to be subject to regulation under environmental statutes, those costs should be considered. Ideally, the environmental costs of a new technology should be examined during its developmental stages. In this manner, the environmental costs and costs of compliance with environmental regulations can be properly integrated into the decision-making process at the research and development stage. Alternative research strategies can then be adopted before a vested interest in protecting the money, time, and effort expended develops. Since photovoltaic solar cells are primarily still in the developmental stages,<sup>15</sup> they are ripe for environmental cost analyses.

The potential for regulatory control of photovoltaics arises in two general areas: the manufacture of the solar cell devices and related equipment; and the placement of the actual devices into the environment. The environmental costs of solar cell manufacture have been examined by others<sup>16</sup> and will not be discussed in this article. The environmental considerations associated with device placement, how-

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13. Experience in other technical areas has shown that the costs of ignoring environmental issues at the outset may pose considerable problems at a later time. The nuclear power industry serves as a classic example. Nuclear power plants have an expected lifetime of 30 to 40 years, at the end of which they must be closed down or, as it is referred to in the nuclear industry, decommissioned. Sefcik, *Decommissioning Commercial Nuclear Reactors*, TECH. REV., June/July, 1979, at 56. As of Nov., 1979, 72 nuclear plants had been built in the United States, *id.* at 58, many of which will have to be decommissioned within the next two decades. *Id.* at 56. Decommissioning and what to do with the radioactive debris was not given much consideration at the time the plants were built. The costs of decommissioning may have to be borne by generations who did not receive the benefits of the power provided by those nuclear plants. *Id.*

14. "Solar cells are electric energy generators that consume no fuel, make no noise, pose no health hazard, and produce no waste products." Loferski, *Photovoltaics I: Solar-Cell Arrays*, IEEE SPECTRUM, Feb. 1980, at 26.

15. In a report prepared at the request of the President's Office of Science and Technology Policy, a panel of leading specialists assembled by the American Physical Society concluded that:

The ultimate prospects [for generating electric power from sunlight] are "bright" but that for at least a decade the technology will not be sufficiently advanced to initiate a major conversion effort.

The group doubts that more than one percent of the nation's electricity can be generated from sunlight by the end of this century.

N.Y. Times, Feb. 1, 1979, at 7, col. 1.

16. Boeninger & Briggs, *Potential Health Hazards in the Manufacture of Photovoltaic Solar Cells*, in HEALTH IMPLICATIONS OF NEW ENERGY TECHNOLOGIES 593 (W. Rom & V. Archer eds. 1980); Coleman, Grenon & Hild, *Environmental Control: An Evaluation of the Economic and Ecological Requirements for the Silicon Photovoltaic Industry*, in THE CONFERENCE RECORD OF THE FOURTEENTH IEEE PHOTOVOLTAIC SPECIALISTS CONFERENCE 1980 at 1042.

ever, have been largely ignored. Those considerations, and especially those associated with the toxicity of some photovoltaic materials, are the topic of this article.

The placement of photovoltaic devices can cause environmental harm in a number of ways. For example, photovoltaic energy collection may require the exclusive use of large areas of land; the generation of electricity may produce waste heat; and the materials used to fabricate the solar cells may be toxic. Such environmental considerations raise questions of the potential costs of the associated environmental harm and compliance with environmental regulatory control.

First, the article will discuss the basics of photovoltaic technology which are necessary for an understanding of the analysis that follows. Next, the article reviews several potential sources of environmental harm associated with solar device placement in the environment. In order to demonstrate the significance of these environmental harms and their potential contribution to the total cost of the technology, the article then focuses on one such source: the toxic nature of some of the materials of which solar cells are fabricated. A brief discussion of the toxic properties of the photovoltaic materials and the ways in which these materials can affect human health and the environment follows. Then, because the recently enacted Toxic Substances Control Act<sup>17</sup> is likely to apply to the manufacture and use of solar cells, the sections of the statute potentially applicable to photovoltaics are examined in depth. Finally, the regulatory framework imposed by the statute is used as a basis to analyze the significance of potential regulatory action on solar cell technology costs.

## II. OVERVIEW OF PHOTOVOLTAICS

### A. *Photovoltaic Technology*<sup>18</sup>

Solar cells are only one part of a complete solar photovoltaic conversion system. The production of such a system consists of a number of steps: the fabrication of solar cells, the mounting of several cells into a solar collector, and the placement of the collector

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17. 15 U.S.C. §§ 2601-2629 (1976 & Supp. III 1979).

18. For a more detailed description of the technology and physical principles involved, see Fan, *Solar Cells: Plugging into the Sun*, TECH. REV., Aug./Sept., 1978, at 14; MERRIGAN, *supra* note 5, at 30-91; 1 OFFICE OF TECHNOLOGY ASSESSMENT, U.S. CONGRESS, APPLICATION OF SOLAR TECHNOLOGY TO TODAY'S ENERGY NEEDS 391 (1978) (U.S. Gov't Printing Office Stock No. 052-003-00539-5) [hereinafter cited as 1 APPLICATION OF SOLAR TECHNOLOGY].

into the environment. A discussion of some of the various methods of performing these steps follows.

### 1. Solar Cell Fabrication

The basic component of a photovoltaic energy system is the solar cell. The cell consists of a thin piece of semiconductor<sup>19</sup> material fabricated in a manner that allows light to interact with the material and produce electricity. As the sun shines on an individual solar cell, the cell generates an electric current. Solar cells can be fabricated in a variety of ways from a number of different semiconductors, resulting in solar cells with different electrical properties. Three semiconductor materials—silicon, cadmium sulfide, and gallium arsenide—have been the subject of most of the research efforts because of their favorable physical and electronic properties.<sup>20</sup> As a result, cells fabricated from these three materials exhibit the best operating characteristics of any tested so far;<sup>21</sup> they will probably be used in the initial photovoltaic energy systems.

Two key factors determine the commercial potential of a solar cell: cell efficiency and cell fabrication costs. Solar cells cannot convert all of the energy present in sunlight into electricity because the physics of the electronic processes within the cell and the effects of the fabrication process limit the efficiency of a solar cell.<sup>22</sup> A solar cell's efficiency is its ability to convert the energy present in the light shining upon it into electrical energy. That efficiency is expressed as the percentage of the energy contained in the incident sunlight that is converted into electrical energy. Efficiency is a critical parameter of a solar cell—the higher the efficiency, the fewer the solar cells needed to produce the desired quantity of electricity. As a result, initial research efforts have focused on materials that yield a solar cell with the highest possible efficiency.<sup>23</sup>

The other critical factor considered by researchers is the cost of producing a solar cell.<sup>24</sup> Some fabrication techniques require numerous painstaking and precise processing steps and therefore

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19. A semiconductor is a material with controllable conductivities intermediate between an insulator and a conductor. L. VANVLACK, *ELEMENTS OF MATERIALS SCIENCE AND ENGINEERING* 484 (3rd ed. 1975).

20. Loferski, *supra* note 14, at 26-27.

21. See Fan, *supra* note 18, at 35.

22. *Id.* at 26.

23. 1 APPLICATION OF SOLAR TECHNOLOGY, *supra* note 18, at 393.

24. *Id.* at 393-94.

result in relatively expensive cells.<sup>25</sup> Other techniques are more adaptable to mass production, requiring less precision and resulting in relatively inexpensive cells.<sup>26</sup> Solar cell efficiency and cost of fabrication tend to be conflicting considerations, however, because higher efficiency solar cells can be manufactured only with the more expensive fabrication techniques.<sup>27</sup>

The fabrication techniques that have been developed for the production of solar cells fall into two broad classes: those using thin films of semiconductor materials<sup>28</sup> and those employing semiconductor wafers.<sup>29</sup> Thin-film solar cells are composed of a very thin layer<sup>30</sup> of semiconductor material sprayed or deposited onto another substance, which provides the supporting base.<sup>31</sup> The deposition techniques are generally quite simple and are adaptable to mass production.<sup>32</sup> Thin-film solar cells contain relatively small quantities of semiconductor material and can be produced inexpensively.

In contrast, solar cells fabricated from semiconductor wafers<sup>33</sup> use much larger quantities of semiconductor material and involve more complex fabrication procedures.<sup>34</sup> The wafers are cut from crystals<sup>35</sup> of the semiconductor which must be carefully grown. During the cutting of the wafers and the associated time-consuming and expensive processing, a considerable quantity of the original semiconductor crystal is wasted,<sup>36</sup> which further adds to the cost of manufacture.

Another solar cell fabrication technique is a hybrid, incorporating both thin-film techniques and a semiconductor wafer.<sup>37</sup> This method, known as epitaxial growth,<sup>38</sup> employs a painstaking process to grow

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25. *Id.* at 400.

26. MERRIGAN, *supra* note 5, at 79-81.

27. *See id.* at 75.

28. Fan, *supra* note 18, at 31-34.

29. *Id.* at 27-31.

30. Thin-film layers are on the order of 1 to 30 micrometers thick (25 micrometers is one thousandth of an inch). *Id.* at 31-33.

31. MERRIGAN, *supra* note 5, at 67-70.

32. *See id.* at 70.

33. Wafers are thin slices of semiconductor material.

34. For a general description of fabrication procedures, *see* Fan, *supra* note 18, at 15, 27-29.

35. Crystals are solids in which the atoms are arranged in an orderly manner. Semiconductor crystals are grown by dipping a seed crystal into a vat of molten semiconductor material, which is maintained at just above its melting point, and then slowly withdrawing the seed. The liquid semiconductor solidifies at the base of the seed as the seed is withdrawn. For a more detailed description of semiconductor crystal growth techniques, *see* 1 APPLICATION OF SOLAR TECHNOLOGY, *supra* note 18, at 412-19.

36. Nearly 50 percent of the crystal is lost as silicon sawdust. *Id.* at 415.

37. Fan, *supra* note 18, at 32.

38. A. GROVE, PHYSICS AND TECHNOLOGY OF SEMICONDUCTOR DEVICES 7-10 (1967).

an ultra-high quality, thin, crystal layer, called an epitaxial layer, of the semiconductor onto a wafer of the same semiconductor material. Although solar cells produced by this method are expensive, they are also the most efficient.<sup>39</sup>

Not all of these cell fabrication techniques are appropriate for every semiconductor material. Thus, the research effort for each of the three semiconductor materials has concentrated on the techniques most appropriate for the particular semiconductor. Gallium arsenide is being used primarily for the development of high-efficiency epitaxial solar cells,<sup>40</sup> cadmium sulfide for thin-film solar cells,<sup>41</sup> and silicon for solar cells fabricated from wafers.<sup>42</sup> Recently some research effort has also been expended in the development of thin-film silicon cells.<sup>43</sup>

## 2. Photovoltaic Solar Collectors

The individual solar cell is only a few square inches in surface area and therefore can only produce a small amount of electric power. Thus, the cells must be assembled into units, called solar collector modules, capable of producing a more significant amount of power. There are two collector types: flat-panel<sup>44</sup> and concentrated-light.<sup>45</sup> The flat-panel collector, the kind most appropriate for rooftop applications, consists of densely packed, electrically interconnected solar cells mounted on a flat supporting structure or panel. The panels are mounted on a building or on their own supporting structure in a fixed position that optimizes the quantity of sunlight reaching the cell as the sun's position in the sky changes with the hour of the day and the season of the year.

An alternative to the flat-panel collector is the concentrated-light collector, which takes advantage of the phenomenon that solar cells operate more efficiently in intense light.<sup>46</sup> A concentrated-light collector consists of a lens positioned over a high-efficiency solar cell. The lens focuses the sunlight onto the cell surface. When the collector is pointed directly at the sun, all of the available light is focused

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39. See Fan, *supra* note 18, at 32.

40. See *id.*

41. Loferski, *supra* note 14, at 27.

42. *Id.* at 26.

43. Carlson, *Photovoltaics V: Amorphous Silicon Cells*, IEEE SPECTRUM, Feb., 1980, at 39.

44. Wolf, *Photovoltaics II: Flat Panels*, IEEE SPECTRUM, Feb., 1980, at 32.

45. Backus, *Photovoltaics III: Concentrators*, IEEE SPECTRUM, Feb. 1980, at 34.

46. Kelly, *Photovoltaic Power Systems: A Tour Through The Alternatives*, 199 SCIENCE 634, 637 (1978).



onto the solar cell. As the sun's position in the sky changes, however, the orientation of the solar collector must also be changed or else all or part of the focused light will miss the solar cell surface, reducing the amount of light that can be converted into electricity. Mechanical systems are used to track the sun, but they add cost and complexity to the collector. These costs and the higher costs of fabricating the high-efficiency solar cells used in concentrated-light collectors can be offset by the cost savings realized from the smaller quantity of solar cells necessary to generate equivalent amounts of power.<sup>47</sup>

### 3. Solar Collector Placement

Once a solar photovoltaic collector has been assembled, it must be placed in the environment so that it can be used to produce electricity. Two approaches have been suggested regarding the placement of collectors: centralized solar farms<sup>48</sup> and decentralized individual solar generating facilities,<sup>49</sup> such as rooftop collectors. The centralized approach requires large areas of land, covering tens of square kilometers,<sup>50</sup> dedicated to massive arrays of photovoltaic solar collectors called solar farms. These farms would most likely be located in the southwestern United States, where land is cheap, sunlight intense, and interference from weather minimal.<sup>51</sup> Because of the large capital investment required to build and operate solar farms, such farms would be owned by utility companies and would connect to existing utility distribution grids.<sup>52</sup> Both flat-panel and concentrated-light collectors could be used on these solar farms.

Decentralized collectors are much smaller in area than consolidated solar farms, covering only tens of square meters rather than millions. Such collectors would be placed in close proximity to the individual user and, in contrast to solar farms, would be subject to his direct control.<sup>53</sup> In fact, most decentralized collectors could be placed on the rooftops of buildings. Both flat-panel and concentrated-light collectors can be used in decentralized applications.<sup>54</sup> Flat-panel col-

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47. *Id.*

48. ENERGY FUTURE, *supra* note 10, at 209.

49. *Id.*

50. To supply a 1000-megawatt base load, approximately 60 square kilometers would have to be dedicated to solar collectors. ECOSYSTEM, *supra* note 4, at 65.

51. MERRIGAN, *supra* note 5, at 23.

52. See ENERGY FUTURE, *supra* note 10, at 209.

53. Some sociologists feel that decentralized solar technologies are more compatible with emerging socioeconomic trends of collective individualism and is more consistent with traditional American values. Daneke, *supra* note 6, at 149.

54. See 1 APPLICATION OF SOLAR TECHNOLOGY, *supra* note 18, at 227-31.

lectors are well suited for sloped-roof applications because the panels can be relatively thin, and with proper architectural design, the angle and orientation of the roof can maximize the collectors' exposure to sunlight.<sup>55</sup> Concentrated-light collectors, however, would not be as readily adaptable for sloped roofs because of the necessity of constantly orienting the collector toward the sun.<sup>56</sup>

There are no economies of scale involved in the generation of electricity with photovoltaic solar cells<sup>57</sup>—a large photovoltaic installation is no more efficient than a small one. Consequently, solar farms appear to present few advantages over decentralized collectors. In fact, some factors, such as the possibility for producing both usable heat and electricity by decentralized collectors, indicate that small decentralized collectors may present advantages over large operations.<sup>58</sup> Such a situation is radically different from that presented by conventional electric energy sources, which offer large economies of scale.<sup>59</sup>

The design of a photovoltaic solar energy system involves trade-offs among a number of factors affecting the final cost of the system.<sup>60</sup> The factors that have generally been considered include the costs of: the solar cells,<sup>61</sup> the necessary supporting structures,<sup>62</sup> and the mechanical orienting devices,<sup>63</sup> as well as energy storage devices, system installation and system maintenance.<sup>64</sup> These factors have determined to a large degree the direction and goals of photovoltaic research.<sup>65</sup> A cost factor which has been only minimally considered, however, and which deserves closer examination is the environmental cost of photovoltaic systems.

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55. Flat-panel collectors, however, may not be appropriate for sloped roofs not facing the direction that receives the most sunlight. *Id.*

56. Because concentrated-light collectors consist of a lens positioned over a solar cell, they are between one and two feet (about 27 to 54 cm) thick. Flat-panel collectors can be less than one inch (2.5 cm) thick. The thickness of concentrated-light collectors and the necessity of moving them as the sun's position changes, makes these collectors more suited for flat roofs.

57. 1 APPLICATION OF SOLAR TECHNOLOGY, *supra* note 18, at 123.

58. Kelly, *supra* note 46, at 642.

59. Loferski, *supra* note 14, at 27-28.

60. Tsou & Stolte, *Effects of Design on Cost of Flat-Plate Solar Photovoltaic Arrays for Terrestrial Central Station Power Applications*, in THE CONFERENCE RECORD OF THE THIRTEENTH IEEE PHOTOVOLTAIC SPECIALISTS CONFERENCE—1978 at 1196.

61. See 1 APPLICATION OF SOLAR TECHNOLOGY, *supra* note 18, at 412-21.

62. Hein, Cusick & Poley, *Impact of Balance of System (BOS) Costs on Photovoltaic Power Systems*, in THE CONFERENCE RECORD OF THE THIRTEENTH IEEE PHOTOVOLTAIC SPECIALISTS CONFERENCE—1978 at 930.

63. *Id.*

64. *Id.*

65. For example, considerable research activity has consistently been directed at increasing the efficiency of those cells fabricated by using inexpensive techniques adaptable to mass pro-

### *B. The Environmental Effects of Solar Photovoltaics*

The large-scale use of photovoltaic solar generating systems is expected to have some adverse environmental effects,<sup>66</sup> such as impacts on the land upon which collectors are located, problems with the disposal of chemicals associated with the production of solar cells, or problems arising from solar energy storage devices. These effects will generally be less severe than those resulting from the use of conventional systems to generate an equivalent amount of electricity.<sup>67</sup> Nevertheless, the environmental effects of photovoltaic collectors should not be dismissed as minimal on this basis alone, because they may still be significant. If these environmental effects are considered early in the design process, they can be reduced or avoided at minimal additional cost. The following discussion will briefly indicate the potential breadth of the environmental problems that can arise from the use of solar photovoltaic technology. One problem in particular, the environmental effects associated with the use of toxic substances in solar cells, will be discussed in depth.

#### 1. Land Use Problems

Centralized solar farms are likely to have significant environmental effects because of the amount and type of land they require. Since an individual solar cell produces only a small amount of electric power, even concentrated-light collectors must be built into huge arrays of solar cells in order to produce enough electric power to meet large-scale demand, such as that of a large city. As a result, considerable land area must be dedicated to solar farms.<sup>68</sup> Such large-scale photovoltaic farms will probably be built in the southwestern United States,<sup>69</sup> a region that is generally an arid, desert-like environment whose ecology is particularly frail.<sup>70</sup> It has been shown that this region can be sensitive even to minor intrusions by man.<sup>71</sup> The effects of a project covering many square kilometers, with its associated roads, vehicles, and maintenance personnel, along with

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duction. Loferski, *Photovoltaics IV: Advanced Materials*, IEEE SPECTRUM, Feb., 1980, at 37. Similarly, methods for growing silicon crystals in thin sheets, which would eliminate the expensive and wasteful process of cutting crystals to produce wafers, are being studied. 1 APPLICATION OF SOLAR TECHNOLOGY, *supra* note 18, at 416.

66. 1 APPLICATION OF SOLAR TECHNOLOGY, *supra* note 18, at 23-24.

67. *Id.*

68. Loferski, *supra* note 14, at 30.

69. See note 50 *supra*.

70. R. Kirk, *Foreword to DESERT—THE AMERICAN SOUTHWEST* (1973).

71. ECOSYSTEM, *supra* note 4, at 48-50.

their residences and recreational activities, would be profound.<sup>72</sup> Local animal habitats and breeding grounds could be disturbed,<sup>73</sup> and it is conceivable that the very existence of some species may be threatened.<sup>74</sup> In addition, water runoff from the photovoltaic panels could cause erosion, affect aquifer supply,<sup>75</sup> or even contaminate the aquifers with chemicals. Furthermore, the panels of the solar collectors must be cleaned periodically of dust and debris in order to provide an unimpaired path for the sun's rays to the solar cell. The detergents or chemicals used for these cleaning purposes, if allowed to drain into the soil, may affect both the local environment and the groundwaters. Although such effects are likely to be especially acute in the arid areas of the southwest, they are not limited solely to those areas. Placed anywhere, a large scale photovoltaic farm will have environmental impacts. Land will have to be cleared, and its use changed.

In contrast, decentralized solar collectors will not produce land use problems of the same magnitude. These collectors are placed in an area that has already been disturbed and where the land has been put to some use. There is no environmental difference whether water drains off a house roof covered with shingles or off a house roof covered with a photovoltaic solar collector. Although the decentralized solar collector may be environmentally less harmful than its centralized counterpart, it is subject to a number of other legal constraints. The myriad of existing zoning ordinances, building codes, and aesthetic requirements have already been successfully used to block the development of some solar projects.<sup>76</sup> Communities desiring to preserve a certain "quality" to their neighborhoods may severely limit or discourage distributed decentralized photovoltaic solar collectors.<sup>77</sup>

## 2. Waste Heat Dissipation

In addition to generating electricity, photovoltaic cells also produce heat which can cause additional environmental problems. The

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72. 1 APPLICATION OF SOLAR TECHNOLOGY, *supra* note 18, at 231.

73. See ECOSYSTEM, *supra* note 4, at 48-49.

74. *Id.*

75. "An aquifer is an underground layer of rock, sand or gravel from which significant quantities of subsurface water can be produced." W. RODGERS, JR., HANDBOOK ON ENVIRONMENTAL LAW 370 (1977).

76. "Initially, the planning committee for Coral Gables, Florida, rejected solar rooftop collectors outright. It then reversed its decision, but set such strict controls on aesthetics that costs were substantially increased." ENERGY FUTURE, *supra* note 10, at 194 (footnotes omitted).

77. For a more complete treatment of land use issues associated with solar energy, see

efficiencies attained by photovoltaic cells range from 6 to 25 percent.<sup>78</sup> Thus, between 75 and 94 percent of the sun's energy shining onto a photovoltaic collector is not converted into electricity. A small fraction of the sunlight will be reflected,<sup>79</sup> but the bulk of the unused energy appears as heat.<sup>80</sup> This heat presents a potential problem in the operation of solar cells because the efficiency of a solar cell decreases with increasing temperature.<sup>81</sup> As a result, the heat generated in the course of a collector's operation must somehow be removed in order to maintain optimal efficiency.

There are two methods of dissipating waste heat: active cooling<sup>82</sup> and passive cooling.<sup>83</sup> Active cooling employs a fluid that is pumped through a network of channels in contact with the solar cell. The heat is transferred from the solar cell to the fluid and is removed by the fluid. The fluid is then cooled in a cooling tower and recirculated, or simply dumped in a body of water and fresh fluid drawn to replace it.<sup>84</sup> By comparison, in passive cooling the heat flows from the solar cell to a heat exchanger with a large surface area, such as a set of fins.<sup>85</sup> The heat exchanger then radiates the heat to the surrounding atmosphere or is cooled by air flow over the heat exchanger surface.<sup>86</sup>

Flat-panel collectors can be designed to operate efficiently by relying solely on passive cooling.<sup>87</sup> In concentrated-light systems, however, so much energy is concentrated onto such a small area that the heat generated usually cannot flow into the heat exchanger rapidly enough to prevent a significant temperature rise of the solar cell. As a result, an active cooling system must usually be used to remove the generated heat.<sup>88</sup>

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Jones, *Aesthetic Restrictions and the Use of Solar Devices*, 8 B.C. ENV. AFF. L. REV. 33 (1979); Zillman & Deeny, *Legal Aspects of Solar Energy Development*, 1976 ARIZ. ST. L. J. 25.

78. Fan, *supra* note 18, at 35. Although a 25 percent conversion rate may seem poor, it should be compared to the efficiency of conventional fossil fuel-fired power plants. The average efficiency of such a plant is 35 percent. Transportation is only about 25 percent efficient. MERRIGAN, *supra* note 5, at 9.

79. Photovoltaic solar cells generally have an antireflective coating on their surface to prevent the reflection of sunlight.

80. 1 APPLICATION OF SOLAR TECHNOLOGY, *supra* note 18, at 395.

81. Kelly, *supra* note 46, at 640.

82. 1 APPLICATION OF SOLAR TECHNOLOGY, *supra* note 18, at 423.

83. *Id.*

84. *See id.* at 424.

85. *Id.* at 423.

86. *Id.* at 424.

87. *Id.* at 423.

88. *See* Edenburn, *Active and Passive Cooling for Concentrating Photovoltaic Arrays*, in THE CONFERENCE RECORD OF THE FOURTEENTH IEEE PHOTOVOLTAIC SPECIALISTS CONFERENCE—1980 at 771.

Waste heat generated by large farms is especially likely to create environmental problems. Concentrated-light collectors used in centralized solar farms will generate tremendous quantities of heat.<sup>89</sup> Since such a facility would be located in a remote area,<sup>90</sup> this heat will not be usable for residential heating or hot water supply, but will have to be disposed of instead. For solar farms located in areas such as the southwestern United States, waste heat disposal will not be a simple matter. This region has relatively few bodies of water available for cooling purposes.<sup>91</sup> Using what little water is available for cooling could cause significant environmental harm because it would raise the water temperature. Raising the water temperature lowers the dissolved oxygen content, increases the toxic effects of certain materials to fish, may affect development, metabolism and reproduction rates, and can present barriers to fish migration.<sup>92</sup>

Waste heat, however, can be used to advantage if a flat-panel or concentrated-light solar collector is employed in a decentralized system. Since decentralized collectors will be located in close proximity to the energy user, the heat can be collected and utilized for residential heating and hot water. This approach, which can increase total energy utilization to nearly 70 percent,<sup>93</sup> accomplishes two objectives—it eliminates the environmental problem of heat disposal, and it provides a substantial economic benefit to the energy user in the form of additional usable energy.

### 3. Energy Storage Problem

Another source of environmental concern arises because solar cells generate electricity only when the sun shines upon them and therefore cannot generate electricity at night or on heavily overcast days. In order to provide electricity during such periods, photovoltaic

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89. A 100-megawatt power plant using 25 percent efficient solar cells will generate about 300 megawatts of heat.

90. Land prices close to a large urban center would preclude the placement of solar farms, requiring many square kilometers, near such centers.

91. The general concept of limited water supply in the southwest is treated in Eisenstadt, *Water Law Problems of Solar Hydrogen Production*, 18 NAT. RESOURCES J. 521 (1978).

92. RODGERS, *supra* note 75, at 525.

93. The 25 kilowatt Fresnel lens photovoltaic concentrator to be built in the Dallas-Fort Worth airport is expected to achieve a 70 percent energy efficiency. The collector will concentrate the sun by a factor of 21.25 and will convert 11.4 percent of the sun's energy into electricity and 58.6 percent into usable thermal energy. O'Neill, *The 25 kw Fresnel Lens/Photovoltaic Concentrator Application Experiment At Dallas-Fort Worth Airport*, in THE CONFERENCE RECORD OF THE FOURTEENTH IEEE PHOTOVOLTAIC SPECIALISTS CONFERENCE—1980.

power sources must have the capability to store energy.<sup>94</sup> A number of systems have been devised to store the electric energy generated by solar cells. They include flywheels, batteries, and systems which use this electricity to produce hydrogen, a clean and efficient fuel, by dissociating water into oxygen and hydrogen.

Each of these systems, however, has its drawbacks. A flywheel employs a heavy spinning mass to store energy. Energy is transferred to a flywheel via an electric motor connected to the shaft. Energy is recovered from a flywheel by activating an electric generator connected to the shaft. Flywheel failure during operation can send large, heavy, high-velocity fragments flying in all directions, posing a serious safety hazard.<sup>95</sup> Safety considerations would therefore require flywheels to be housed underground,<sup>96</sup> which in turn could cause other environmental problems. Batteries pose a serious environmental hazard during use and upon disposal because they commonly contain toxic metals, such as lead and cadmium, are filled with corrosive chemicals, such as sulfuric acid, and can evolve toxic fumes during use.<sup>97</sup> The dissociation of water to obtain hydrogen requires large quantities of water<sup>98</sup> which are unlikely to be available. Removing this water from the environment may have severe local impacts or even be prohibited by existing water usage laws.<sup>99</sup> Additional supplies of water could be obtained by desalinating underground brine,<sup>100</sup> but the need to dispose of the salt residue could cause a solid-waste disposal problem. Unless properly disposed of or put to some commercial use, the salt could contaminate fresh surface waters or topsoil, or be dispersed into the air.

### C. Toxicity of Photovoltaic Materials

Solar cells raise additional environmental concerns because of the toxicity of some of the semiconductor materials they are fabricated of. Toxicity is defined as the "ability of a chemical to cause injury once it reaches a susceptible site in or on the body."<sup>101</sup> Toxicity in-

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94. 1 APPLICATION OF SOLAR TECHNOLOGY, *supra* note 18, at 427-83.

95. Millner, *Flywheels for Energy Storage*, TECH. REV., Nov., 1979, at 33.

96. *Id.*

97. 1 APPLICATION OF SOLAR TECHNOLOGY, *supra* note 18, at 472.

98. For a discussion of the quantities of water involved, see Eisenstadt, *supra* note 91, at 523.

99. *Id.* at 525.

100. *Id.* at 537.

101. Durham, *Toxicology*, in DANGEROUS PROPERTIES OF INDUSTRIAL MATERIALS 271, 272 (N. Sax ed., 5th ed., 1979). A legal definition of "toxic" is: TOXIC—"Poisonous; having the character of producing the effects of a poison; referable to a poison; produced by or resulting from a poison." BLACK'S LAW DICTIONARY 1337 (5th ed., 1979).

cludes not only the ability of a chemical to cause death from oral ingestion, but also the ability to cause illness by any interaction of the chemical with the body, such as through inhalation or by mere contact with the skin. Other toxic effects, not generally considered to be within the popular definition of toxicity, include the chemical's ability to induce cancer (carcinogenesis), cause transmissible genetic damage (mutagenesis), or cause birth defects (teratogenesis). The various semiconductor materials used to make photovoltaic cells—silicon, gallium arsenide, and cadmium sulfide—exhibit some or all of these toxic properties to varying degrees.<sup>102</sup>

## 1. Toxic Properties of Semiconductors<sup>103</sup>

### a. Silicon

Silicon<sup>104</sup> is generally considered to be non-toxic.<sup>105</sup> If heated and allowed to contact air, silicon reacts at temperatures above 700°C (about 1300°F) to form silicon dioxide,<sup>106</sup> a compound also known as

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102. The scientific community has expressed some concern over the toxic properties of some photovoltaic semiconductors.

Enthusiasm about cells based on materials other than silicon must be tempered to some extent by uncertainties about the health hazards that they may present . . . .

Both CdS [cadmium sulfide] and GaAs [gallium arsenide] contain toxic materials, and, although it may be possible to reduce the hazards they present to manageable proportions, it clearly will be necessary to examine this issue with some care before their widespread use can be contemplated.

Kelly, *supra* note 46, at 637.

103. Under the proper conditions and dosages, nearly all materials can be toxic. There exists, however, a system for categorizing the hazards of chemical substances. The term LD<sub>50</sub> designates the amount necessary to constitute a lethal dose to 50 percent of a specified population. It is expressed in milligrams of the chemical substance per kilogram of body weight of the test subject. The following categories are used:

- High Toxicity: LD<sub>50</sub> = 500 mg per kg or less. Exposure in normal use capable of causing death or permanent injury.
- Moderate Toxicity: LD<sub>50</sub> = 500 to 7500 mg per kg. Exposure in normal use may cause considerable discomfort and reversible or irreversible changes to tissue, but not permanent injury or death.
- Low Toxicity: LD<sub>50</sub> = 7500 to 15,000 mg per kg. Exposure may cause some discomfort and readily reversible tissue changes that disappear after exposure stops.
- No Toxicity: LD<sub>50</sub> = 15,000 mg per kg or more. No harm from exposure during normal use. Harmful only due to overwhelming dose or unusual condition.

Sax, *Preface* to DANGEROUS PROPERTIES OF INDUSTRIAL MATERIALS at vii (N. Sax ed. 5th ed. 1979); Sax, *General Chemicals*, in *id.*, 325, 330.

104. The element silicon should not be confused with silicone, which is a member of a class of chemicals containing hydrogen, silicon, and other elements, or silica, which is actually the compound silicon dioxide.

105. Kelly, *supra* note 46, at 637.

106. H. WOLF, SILICON SEMICONDUCTOR DATA 532 (1969).



silica, and which is identical to ordinary beach sand.<sup>107</sup> Silicon dioxide is associated with silicosis, a serious lung disease.<sup>108</sup> Silicosis, however, requires chronic exposure to very fine silicon dioxide dust for periods of ten to twenty-five years,<sup>109</sup> a situation which would not arise during the use of silicon solar cells. Thus, silicon presents no serious hazard to either humans or the environment.

#### b. Gallium Arsenide

Gallium arsenide is moderately toxic<sup>110</sup> and may also be carcinogenic.<sup>111</sup> When heated and exposed to air at temperatures above 600°C (about 1100°F), such as could occur in a normal fire, gallium arsenide oxidizes, producing arsenic trioxide and gallium oxide.<sup>112</sup> Gallium oxide apparently does not present a toxicity problem, since animal experiments suggest low toxicity.<sup>113</sup> Arsenic trioxide, however, is highly toxic,<sup>114</sup> carcinogenic,<sup>115</sup> and possibly mutagenic and teratogenic.<sup>116</sup> Arsenic trioxide is readily soluble in water,<sup>117</sup> and thus could enter water supplies. Since arsenic trioxide would be formed under certain conditions from the gallium arsenide used in photovoltaic solar cells, a toxicity problem exists for gallium arsenide.

#### c. Cadmium Sulfide

Cadmium sulfide is highly toxic.<sup>118</sup> Cadmium and cadmium compounds are suspected carcinogens,<sup>119</sup> and cadmium sulfide has been included by the Environmental Protection Agency (EPA) in a list of

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107. Sax, *supra* note 103, at 968, 969.

108. Sax, *supra* note 103, at 968. To cause silicosis, however, the silica must be inhaled as dust.

109. THE INTERNATIONAL TECHNICAL INFORMATION INSTITUTE, TOXIC AND HAZARDOUS INDUSTRIAL CHEMICALS SAFETY MANUAL 462 (1976).

110. Oral LD<sub>50</sub>(rat) = 4700 mg per kg. Sax, *supra* note 103, at 700.

111. The Carcinogens Assessment Group, Office of Health and Environmental Assessment in EPA's Research and Development Office, has prepared a list of chemical substances having substantial evidence of carcinogenicity. Arsenic and arsenic compounds are included in this list. *List of Chemicals Having Evidence of Carcinogenicity, Prepared by EPA Carcinogen Assessment Group*, 4 CHEM. REG. REP. 647, 648 (1980).

112. Minden, *Thermal Oxidation of GaAs*, 109 J. ELECTROCHEM. SOC'Y. 733 (1962).

113. Sax, *supra* note 103, at 701.

114. Oral LD<sub>50</sub>(man) = 1.43 mg per kg. *Id.* at 390.

115. See note 111 *supra*.

116. Dickerson, *Arsenic*, in METALS IN THE ENVIRONMENT 1, 16 (H. Waldron ed. 1980).

117. See CRC, HANDBOOK OF CHEMISTRY AND PHYSICS at B-79 (R. Weast ed., 61st ed. 1980)

118. No LD<sub>50</sub> data was located. Sax indicates, however, that cadmium and its compounds are highly toxic. Sax, *supra* note 103, at 456.

119. *List of Chemicals, supra* note 111, at 648.

ten chemicals considered of greatest interest for carcinogenicity testing.<sup>120</sup>

When heated in air, cadmium sulfide oxidizes to produce cadmium sulfate, basic cadmium sulfate, and cadmium oxide, with some cadmium sulfide remaining, depending on reaction temperature.<sup>121</sup> At reaction temperatures below 700°C (about 1300°F), the sulfate products dominate;<sup>122</sup> at temperatures above 700°C, cadmium oxide is the main reaction product<sup>123</sup> evolving as fumes. Cadmium oxide fumes are extremely toxic.<sup>124</sup> Human exposure to these fumes is especially sinister, because the inhalation of cadmium oxide fumes does not produce immediate symptoms.<sup>125</sup> Therefore, a victim may be exposed to lethal doses of cadmium oxide fumes without being aware of it or experiencing any discomfort.<sup>126</sup> The fumes are so toxic that during World War II the potential of cadmium oxide fumes as a weapon was considered.<sup>127</sup> Cadmium sulfate is also highly toxic.<sup>128</sup> Both cadmium oxide<sup>129</sup> and cadmium sulfate<sup>130</sup> are highly soluble in water. Thus, they can readily spread throughout the environment and contaminate water supplies. Cadmium contamination of drinking water is responsible for the painfully crippling "itai-itai" disease in Japan.<sup>131</sup> Because of these toxicity dangers, cadmium sulfide presents perhaps the greatest hazard of all the materials used in photovoltaic solar cells.

## 2. Entry Routes

While these semiconductor materials may be toxic, their toxicity needs to be considered in the economic analysis of photovoltaic solar

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120. *EPA Recommends 10 Chemicals for Priority Testing Under NTP*, 4 CHEM. REG. REP. 256 (1980).

121. D. CHIZHIKOV, *CADMIUM* 27 (1966).

122. *Id.*

123. *Id.*

124. The time-dependent lethal dose of cadmium oxide fumes is estimated at 1900 min-mg/m<sup>3</sup> (minutes milligrams per cubic meter), with some investigations indicating considerably lower lethal dosages. A lethal exposure is calculated by considering the duration of the exposure and the concentration of the fumes. Thus, for cadmium oxide, a 10-minute exposure to air containing 190 mg of cadmium oxide fumes per cubic meter would be lethal; likewise, 20 minutes at 95 mg per cubic meter would be lethal. Yasamura, Vartsky, Ellis & Cohn, *Cadmium in Human Beings*, in *CADMIUM IN THE ENVIRONMENT* 12, 13-14 (J. Nriagu ed. 1980).

125. *Id.* at 14.

126. *Id.*

127. *Id.* at 12.

128. Intraperitoneal LD<sub>50</sub>(mouse) = 7 mg per kg. *REGISTRY OF TOXIC EFFECTS OF CHEMICAL SUBSTANCES* 297 (R. Lewis ed. 1978).

129. CHIZHIKOV, *supra* note 121, at 12.

130. CRC, *supra* note 117, at B-86.

131. Translated from the Japanese, "itai-itai" means "it hurts" or "ouch-ouch." The symp-

cells only to the extent that these materials or their toxic by-products can enter the environment or come into contact with humans. Only to that extent can an economic impact due to their toxicity be expected.

Once a solar photovoltaic system is installed, contact of the semiconductor materials with humans and the environment can occur in one or more of the following ways: (1) direct contact of the solar cell with its ambient environment, such as by rain or wind; (2) accidental damage to, or destruction of, the photovoltaic generating facility by events such as fire, lightning, or earthquakes; or (3) planned destruction of the facility upon the completion of its useful life.

Contamination of the environment through direct contact of the semiconductor material with air, rain, plants, animals, or humans during the normal operation of the solar collector is highly improbable, because the solar cells are coated to prevent such contact. The electronic processes occurring within the solar cell are highly sensitive to the status of the solar cell surface.<sup>132</sup> Any number of materials found in nature, if allowed to come into contact with the surface, can drastically reduce the efficiency of the solar cell and, therefore, its electrical output. As a result, solar cells are carefully encapsulated to prevent any direct contact with the environment other than exposure to sunlight. In effect, this provides dual protection: protection of the solar cells' efficiency and protection of the environment.

Nevertheless, contact with the environment could occur as the result of a natural or man-made disaster. Such an event could damage a substantial fraction of the encapsulant and allow the semiconductor material to become exposed. The resulting degree of environmental harm and effects on humans would depend on the toxicity of the materials, their solubility in water or the weak acids found in nature,<sup>133</sup> and the quantity of the material that became ex-

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toms of the disease, caused by the ingestion of water contaminated by cadmium, are severe bone pain in the back and legs, difficulty in walking, and deformity in the pelvis, spine, and legs. Fassett, *Cadmium*, in METALS IN THE ENVIRONMENT 61, 101-02 (H. Waldron ed. 1980).

132. See, e.g., Slusarczuk, Study of Electronic and Optical Properties of Gallium Arsenide Surfaces and Interfaces (September 1979) (unpublished doctoral thesis, Massachusetts Institute of Technology Library).

133. An example of such an acid is acid rain, a weak solution of sulfuric acid formed from the reaction of atmospheric sulfur dioxide with rain droplets. Both cadmium sulfide, CHIZHIKOV, *supra* note 121, at 25, and gallium arsenide, CRC, *supra* note 117, at 101, are insoluble in water, while the combustion products arsenic trioxide, cadmium sulfate, and cadmium oxide, are readily soluble in water. See text at notes 117, 129, 130 *supra*.

posed. Materials of low solubility present minimal hazard since they cannot readily enter the environment.

A fire at a photovoltaic installation is the most serious type of disaster that could occur, because it not only could release the semiconductor material into the environment but also could cause chemical reactions to take place, producing additional toxic chemicals.<sup>134</sup> Decentralized photovoltaic collectors mounted on buildings are particularly susceptible to fire damage, since the buildings upon which they are mounted can burn, providing the temperatures necessary for oxidation reactions to take place. Furthermore, if the building is located in a densely populated area, as it often will be, the chemical vapors released in a fire can easily affect the occupants of the building, neighbors, and firefighters. These chemical vapors will eventually condense and settle in the surrounding area, providing a source of continued exposure to humans and the environment.

Fire is not as serious a threat with centralized solar farms, because collectors mounted on structures dedicated solely to supporting photovoltaic cell collectors can readily be protected from fire. The structural materials can be chosen to be nonflammable or can be treated with fire retardants. In this way, the temperatures necessary for the chemical reactions to take place can be avoided.

In addition to the possible fire hazards, photovoltaic materials may also present disposal problems when a solar facility is destroyed at the end of its useful life. Although there are no moving parts to wear out, the solar cells or the encapsulating material may degrade with time, due in part to temperature cycling.<sup>135</sup> As a result, their efficiency slowly decreases with age. The spent cells can either be disposed of or recycled. Whether the materials are recycled depends upon the relative cost of recycling and the value of the recycled material. Thin-film solar cells containing relatively small amounts of inexpensive semiconductor materials are not likely to be recycled. If

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134. See text and notes at notes 112-16 and 121-28 *supra*. A calculation of the quantity of chemicals that would be contained in rooftop collectors suggests a hazard. If a rooftop collector were to provide five kilowatts of peak electric power using 10 percent efficient cadmium sulfide solar cells, approximately 50 square meters of cell area would be required. If the cells were composed of a 25 micrometer-thick layer of cadmium sulfide, the collector would contain about six kilograms of cadmium sulfide. Assuming that during a fire only cadmium oxide would be formed, the solar collector would produce about 5.4 kilograms of cadmium oxide. Since the time dependent lethal dose for cadmium oxide is 1.9 grams-minutes per cubic meter of air, see note 124 *supra*, such a collector mounted on a rooftop could, during a fire, cause serious injury to persons in close proximity to the fire.

135. MERRIGAN, *supra* note 5, at 72; ECOSYSTEM, *supra* note 4, at 51.

not recycled, spent solar cells would have to be disposed of. Improper disposal of the cells can be harmful to the environment and humans, because if the cells were incinerated they could release toxic vapors; and if they were placed in a landfill with other chemicals, there is the possibility of chemical reactions which could form soluble toxic compounds, which could then leach into aquifers.

Of all the possible routes by which the photovoltaic materials and their toxic byproducts could enter the environment, the danger of a disaster by fire is the most serious. The potential for harm to humans and the environment depends on the toxic properties and solubilities of the semiconductor materials used in the solar cells, their oxidation products, the quantity of semiconductor material exposed to the fire and the proximity of people to the disaster.

The price of the environmental damage which could be caused by the toxic materials in photovoltaic solar cells can encompass both economic and social costs. Social costs are borne by society at large and are difficult to quantify. They include such factors as the loss of human life, the loss of health, and the shortening of expected lifespan due to poisoning as well as the physical and mental suffering associated with these losses. The costs extend beyond direct injury to humans to include those resulting from the diminution of the quality of life: the loss of such benefits as swimming, fishing, and readily available drinking water<sup>136</sup> which derive from our natural resources. There exists a possibility that society may not be willing to bear these costs and may, through demonstrations, boycotts, pressure on legislative representatives, or other actions, prevent the large-scale implementation of solar photovoltaics.<sup>137</sup>

Environmental damage can introduce significant economic costs to both the manufacturer and society. If a causal connection between the manufacturer of the solar cell and the injury to health or to the environment can be established, the manufacturer can become liable for tort damages. Litigation, settlement, and damage costs can be substantial.<sup>138</sup> If equitable relief is granted, the manufacturer may have to undo the environmental harm for which he was responsible.

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136. Cadmium contamination of water supplies is responsible for the "itai-itai" disease. See note 131 *supra*. Arsenic contamination of drinking wells has recently raised concerns in Massachusetts and New Hampshire. *Boston Globe*, Feb. 24, 1981, at 17, col. 1.

137. It should be noted, however, that at present solar energy is favorably received by the general public.

138. On March 28, 1979, the nuclear reactor at Three Mile Island was the site of the worst accident at a United States commercial nuclear reactor. A \$25 million settlement has been tentatively approved for the economic claims of people living around the nuclear plant. *Boston Globe*, Feb. 22, 1981, at 30, col. 1.

On the other hand, if liability for the damage cannot be placed on the manufacturer, or if the manufacturer has since gone bankrupt, dissolved, or simply does not have the assets to cover the damages, society as a whole will have to bear the cost.

A similar situation has arisen with hazardous waste chemicals.<sup>139</sup> Large quantities of highly toxic chemicals stored in deteriorating containers are repeatedly being discovered. Frequently the owners of the chemicals cannot be located or the disposal company which has placed the chemicals into the environment has since dissolved. Thus, society must bear the cost of properly disposing of these chemicals or else the people face possible injury to health. Thus, before photovoltaics are introduced into the environment their toxic potential should be fully understood and, where possible, minimized.

### III. REGULATORY CONTROL OF PHOTOVOLTAIC MATERIALS

In addition to the possible costs associated with direct physical harm due to semiconductor toxicity, costs may also be incurred because of the regulatory scheme that may be invoked by that toxicity. Because the costs associated with regulatory control may alter the economic outlook for photovoltaics and raise questions about their viability, the nature of the regulatory framework must be examined.

Congress has officially recognized solar photovoltaics as a significant component of the national energy program by enacting the Solar Photovoltaic Energy Research, Development, and Demonstration Act of 1978.<sup>140</sup> In addition, other statutes contain provisions encouraging the development of solar photovoltaics.<sup>141</sup> Congress, how-

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139. Magnuson, *The Poisoning of America*, TIME, Sept. 22, 1980, at 58.

140. 42 U.S.C. §§ 5581-5594 (Supp. III 1979). In its declaration of policy, Congress expressed its hope that "the early development and widespread utilization of photovoltaic energy systems could significantly expand the domestic energy resource base of the United States, thereby lessening its dependence on foreign supplies." *Id.* § 5581(a)(5).

The statute sets out a ten-year program with an objective of doubling the production of photovoltaic systems each year for ten years so as to reach an annual United States production of 2,000 megawatts by 1988. *Id.* § 5581(b). One-and-a-half billion dollars are to be spent by the government over the next ten years to achieve this goal. *Id.* § 5581(a)(21).

141. The Foreign Service Buildings Act, 22 U.S.C. §§ 291-301 (1976), was amended in 1978 to include provisions for incorporating solar photovoltaics in foreign service buildings as a demonstration of solar and other renewable energy technologies in foreign countries. 22 U.S.C. § 292a(b)(1) (Supp. III 1979). This statute is intended to have the additional effect of developing markets for American solar energy systems. *Id.* § 292a(a)(2).

The Small Business Energy Loan Act, 15 U.S.C. §§ 633, 636, 639 (Supp. III 1979), includes provisions empowering the Small Business Administration to make loans to small business concerns in order to assist them in entering the solar photovoltaic market. *Id.* § 636(l)(1).

ever, has also passed environmental legislation such as the Toxic Substances Control Act,<sup>142</sup> the Clean Air Act,<sup>143</sup> the Clean Water Act,<sup>144</sup> and the National Environmental Policy Act,<sup>145</sup> that could have the effect of slowing the development of photovoltaics.<sup>146</sup> Because the manufacture of solar cells requires the use of chemical substances that can have adverse environmental effects, the photovoltaic industry falls within the scope of the Toxic Substances Control Act. This Act could lead to substantial restrictions on the development of photovoltaics. Therefore, the sections of the statute that could affect the use of the three semiconductor materials used in solar cells—gallium arsenide, silicon, and cadmium sulfide—will be examined in detail here.<sup>147</sup>

### A. *The Toxic Substances Control Act*

The Toxic Substances Control Act (TSCA), imposes broad regulatory control not just over toxic substances, as its name would imply,<sup>148</sup> but rather over the chemical manufacturing industry as a whole and any company that incorporates chemical substances into its products. Congress enacted TSCA in response to a growing concern over the rapidly increasing quantity of, and relative ignorance about, chemical substances and mixtures potentially harmful to humans and the environment.<sup>149</sup> The statute was designed to fill a number of regulatory gaps by providing the opportunity for regula-

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The Internal Revenue Code includes a tax credit for solar photovoltaic collectors installed on principal residences as an incentive to potential consumers of the technology. I.R.C. § 44C.

142. 15 U.S.C. §§ 2601-2629 (1976 and Supp. III 1979).

143. 42 U.S.C. §§ 7401-7642 (Supp. III 1979).

144. 33 U.S.C. §§ 1251-1376 (1976 and Supp. III 1979).

145. 42 U.S.C. §§ 4321-4369 (1976 and Supp. III 1979).

146. Since a solar photovoltaic farm could be subjected to federal licensing as a power utility before it could be built, the National Environmental Policy Act (NEPA) would likely require the preparation of an Environmental Impact Statement (EIS) assessing possible environmental harm. The Clean Air Act and Clean Water Act might also have an impact by regulating effluents of the solar cell fabrication facility, thereby increasing solar cell manufacture costs.

147. The complete act has been discussed in several articles. See, e.g., Zener, *The Toxic Substances Control Act: Federal Regulation of Commercial Chemicals*, 32 BUS. LAW. 1685 (1977); Gaynor, *The Toxic Substances Control Act: A Regulatory Morass*, 30 VAND. L. R. 1149 (1977); Druley & Ordway, *The Toxic Substances Control Act*, 7 ENVIR. REP. (BNA) (Monograph No. 24) (1977).

148. The name of the Act, Toxic Substances Control Act, is rather misleading. The scope of the Act is much broader than the name itself implies, as the Act's coverage extends well beyond merely toxic substances. The only place other than the title that the word toxic appears is in section 10(d), 15 U.S.C. § 2609(d). TSCA is directed at chemical substances, mixtures and activities involving chemicals and mixtures which can present an unreasonable risk of injury to health or the environment.

149. H.R. REP. NO. 1341, 94th Cong., 2d Sess. 3 (1976).

tory control over chemical substances prior to their introduction into the environment, during their use, and upon their disposal at the end of their useful life.<sup>150</sup> Although TSCA provides for strict regulatory control of chemicals, it has not yet been fully implemented.<sup>151</sup>

Under TSCA, the critical determination to be made by the Environmental Protection Agency (EPA) is whether a substance presents an "unreasonable risk of injury to health or the environment."<sup>152</sup> If a substance presents such a risk, the EPA has broad authority to regulate its manufacture and use, based upon a balancing of risk with the potential benefits. Passage of the Act was not intended to remove all risks associated with the use of chemicals.<sup>153</sup> Nor was the statute intended to create unnecessary economic barriers or to impede technological innovation.<sup>154</sup> Rather, Congress intended that TSCA be implemented in a reasonable and prudent manner, considering economic and social, as well as environmental, impacts.<sup>155</sup>

### 1. The Regulatory Scheme of TSCA

The EPA's power to regulate chemical substances and mixtures<sup>156</sup> is based upon their potential effect on human health and the environment. The term "environment" is defined broadly to include water, air, land, and the interrelationship that exists among them, as well as

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150. *Id.* at 6.

151. The Toxic Substances Control Act was enacted in October, 1976. Early in 1977, the Environmental Protection Agency presented an approach to implementing TSCA. The approach established four priority areas for implementation activities during the first several years: (1) the establishment and implementation of a premarket review system; (2) the establishment of initial testing requirements; (3) regulatory actions to control a limited number of environmental problems associated with existing chemicals; (4) assessment and control of unanticipated problems of urgent concern. OFFICE OF TOXIC SUBSTANCES, U.S. ENVIRONMENTAL PROTECTION AGENCY, ASSESSMENT AND CONTROL OF CHEMICAL PROBLEMS—AN APPROACH TO IMPLEMENTING THE TOXIC SUBSTANCES CONTROL ACT 7-8 (Draft No. 3, 1977). Although TSCA has been in effect for over five years, the EPA's stated implementation objectives have only been partially fulfilled. Organizational and staffing problems and no clear sense of direction have been blamed for this lack of progress. See The Comptroller General of the U.S., Report to the Congress, EPA is Slow to Carry Out Its Responsibility to Control Harmful Chemicals (Oct. 28, 1980).

152. 15 U.S.C. § 2601(b)(2) (1976). The term "unreasonable risk of injury to health and the environment" appears throughout the statute.

153. H.R. REP. No. 1341, *supra* note 149, at 15.

154. 15 U.S.C. § 2601(b)(3) (1976).

155. *Id.* § 2601(c).

156. Throughout this article the term chemical substance will be used to refer to "chemical substances and mixtures." Sections of the statute that do not apply to mixtures will be so noted.



all living things.<sup>157</sup> "Chemical substance" is also defined broadly to include any organic or inorganic substance, element, uncombined radical, or any combination of such substances that is the result of a chemical reaction or that occurs in nature.<sup>158</sup> TSCA specifically excludes from its coverage pesticides, tobacco, nuclear materials, fire-arms, ammunition, food, food additives, drugs, and cosmetics.<sup>159</sup>

The semiconductor materials, silicon, gallium arsenide, and cadmium sulfide, are clearly within the scope of TSCA, since silicon is an element, and gallium arsenide and cadmium sulfide are inorganic compounds, none of which are covered by any exemption. Furthermore, solar collectors will be located in the "environment" which the toxic materials may potentially affect. Consequently, the materials may be subjected to one or more provisions of TSCA.

There are two key elements to the regulatory scheme of TSCA. The first, the development of adequate data concerning the effects of chemical substances on health and the environment,<sup>160</sup> is embodied in sections 4,<sup>161</sup> 5,<sup>162</sup> and 8<sup>163</sup> of the statute. The second, the regulation of activities involving those chemical substances found to present an unreasonable risk of injury or imminent hazard to health or the environment,<sup>164</sup> is embodied in sections 6<sup>165</sup> and 7<sup>166</sup> of the statute. Section 6 provides the EPA with a range of regulatory options which enable it to control all phases of a chemical's life. Section 7 provides the EPA with emergency powers for the regulatory control of imminently hazardous chemicals. TSCA places the burden of developing the data necessary to implement the statute upon the manufacturers of the chemical substances,<sup>167</sup> and authorizes a number of mechanisms by which the EPA may obtain that data. The data obtained provides the EPA with the basis for determining what regulatory measures are necessary for a particular substance.

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157. *Id.* § 2602(5).

158. *Id.* § 2602(2). A mixture is defined as a combination of two or more chemical substances not occurring in nature and not the result of a chemical reaction. *Id.* § 2602(8). Thus, the definition of chemical substances and mixtures is broad enough to place iron and steel products, metal alloys, crude oil, natural gas, minerals, ores and other materials not commonly considered "chemicals" within the regulatory scope of the statute. H.R. REP. NO. 1341, *supra* note 149, at 44.

159. 15 U.S.C. § 2602(2)(B) (1976). Congress felt these classes of items were better regulated by other statutes. *See* H.R. REP. NO. 1341, *supra* note 149, at 10-12.

160. 15 U.S.C. § 2601(b)(1) (1976).

161. *Id.* § 2603.

162. *Id.* § 2604.

163. *Id.* § 2607.

164. *Id.* § 2601(b)(2).

165. *Id.* § 2605.

166. *Id.* § 2606.

167. *Id.* § 2601(b)(1).

### a. Data Gathering

The core data-gathering provisions of TSCA are embodied in sections 4, 5, and 8. Each of these sections establishes a mechanism by which the EPA can gather data. Section 8 requires the manufacturers, processors, and distributors of the chemical substances to maintain records and submit reports to the EPA concerning the adverse effects of chemical substances on health and the environment. Section 5 requires the manufacturers of new chemical substances, and those who put existing substances to significant new uses, to notify the EPA prior to commercial manufacture. Section 4 directs the EPA, under certain conditions, to require the testing of a chemical substance by the manufacturer in order to obtain the necessary data. Each of these sections will be examined in turn.

The general information-gathering provisions of section 8 lay the groundwork for the EPA's subsequent regulatory actions under other sections of TSCA.<sup>168</sup> Subsection 8(a) is the basic reporting provision, requiring manufacturers to submit to the EPA reports detailing the chemical's name, amounts manufactured, and data on health and environmental effects, and the scope of human exposure to the substances.<sup>169</sup> Subsection 8(c) places an obligation on manufacturers, processors, and distributors to maintain records of any significant adverse health or environmental effects.<sup>170</sup> These record-keeping requirements are stringent.<sup>171</sup> Under subsection 8(d) a manufacturer, processor, or distributor must submit to the EPA the results of any health or safety studies,<sup>172</sup> and this provision has been strictly interpreted.<sup>173</sup> Subsection 8(e) requires manufacturers, proc-

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168. Section 8 refers to chemical substances only, and therefore does not include mixtures.

169. 15 U.S.C. § 2607(a) (1976). The reports are to include the common or trade name, chemical identity, molecular structure, category, amounts involved, byproducts, amount and duration of the exposure to humans, an estimate of the number of humans that will be exposed, all existing data concerning the environmental and health effects, and the manner of disposal. *Id.* § 2607(a)(2). Rules specifying who must report and what specifically must be included in the report have been promulgated. 40 C.F.R. § 710 (1980).

170. 15 U.S.C. § 2607(c) (1976).

171. Manufacturers, processors, and distributors are required to maintain records of any significant adverse health effects to employees for 30 years. *Id.* Records of consumer allegations of harm or injury, reports of occupational disease, and complaints of environmental harm must be retained for five years. *Id.*

172. *Id.* § 2607(d).

173. *Dow Chemical Co. v. EPA*, 605 F.2d 673 (3d Cir. 1979). In that case, the Dow Chemical Co. challenged a rule promulgated under section 8(d). The rule required manufacturers to submit to the EPA studies of chemicals used solely for product research and development. The court upheld the agency's assertion of authority, holding that product research and development constituted a commercial purpose and was therefore subject to the rule implementing the

essors, and distributors to submit immediately to the EPA any information that reasonably supports the conclusion that the chemical substance presents a substantial risk of injury to health or the environment.<sup>174</sup> In turn, subsection 8(b) imposes an obligation on the EPA to compile and maintain an inventory of all chemicals currently manufactured or processed within the United States, based on the information submitted pursuant to section 8.<sup>175</sup>

Section 8 will not impose significant economic burdens on the solar photovoltaic industry. The record-keeping requirements imposed by subsection 8(c) may place some economic burdens on the manufacturers of photovoltaic solar cells and collectors. The compliance costs will, however, be mainly clerical, associated with the recording and filing of information, and thus will not likely have a significant impact on the development of photovoltaics. Compliance with subsection 8(d) requires the submission of existing studies. Since no new studies need be initiated, the costs to the manufacturer will be minimal. The reporting requirement of subsection 8(e) will directly involve only minimal costs, but the long-term ramifications of this subsection may be to trigger regulatory action under one of the other sections of TSCA,<sup>176</sup> which conceivably could create substantial indirect costs.

While section 8 provides the EPA with information on existing chemicals and their current uses, the premanufacture notification requirements of section 5 apply to new chemicals and new uses for existing chemicals. A manufacturer planning to introduce a new chemical substance,<sup>177</sup> or a manufacturer or processor who plans to subject an existing substance to a significant new use,<sup>178</sup> is directed to provide the EPA with a notice of that intent at least 90 days prior to manufacture,<sup>179</sup> accompanied by data showing that the activity

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requirements of subsection 8(d). *Id.* at 686. See also *TSCA and Trade Secrets: Third Circuit Upholds EPA's Broad Authority to Obtain Health Studies Under § 8(d)*, 9 ENV'T L. REP. 10,163 (1979).

174. See generally Kahan, *Reporting Substantial Risks Under Section 8(e) of the Toxic Substances Control Act*, 19 B.C. L. REV. 859 (1978).

175. 15 U.S.C. § 2607(b) (1976). This inventory is to serve as the basis for determining the premarket notification obligations of manufacturers and processors under section 5. *Id.* § 2604(a)(1)(A). The inventory has been compiled and published by the EPA. OFFICE OF TOXIC SUBSTANCES, U.S. ENVIRONMENTAL PROTECTION AGENCY, TOXIC SUBSTANCES CONTROL ACT (TSCA) CHEMICAL SUBSTANCES INVENTORY (1979 and Cumulative Supp. 1980). It comprises four large volumes listing names of chemical substances and two volumes of trademark and product names. The inventory is updated annually to include the names of new chemical substances introduced into the market.

176. See text and notes at notes 215-42 *infra*.

177. 15 U.S.C. § 2604(a)(1)(A) (1976).

178. *Id.* § 2604(a)(1)(B).

179. *Id.* § 2604(a).

will not create an unreasonable risk.<sup>180</sup> The EPA may, for good cause, increase the time period before which manufacturing may begin.<sup>181</sup> A new chemical substance is one not appearing in the EPA's inventory listing the chemical substances currently manufactured or processed in the United States.<sup>182</sup> A significant new use of an existing substance must be determined by the EPA by promulgation of a rule.<sup>183</sup> The EPA's criteria for determining what constitutes a significant new use and the EPA's premanufacture notification requirements and review procedures are still in the proposed-rule stage and are constantly being revised.<sup>184</sup> Thus, it is difficult to determine the potential effect of section 5's reporting requirements on the development of photovoltaics.

To the extent that this section is applicable to photovoltaics, however, its effect would be to delay<sup>185</sup> the introduction of solar cells into the market and their subsequent placement into the environment. The economic costs of such delays may be significant. A manufacturer who is committed to solar cell production will incur fixed overhead costs during the time that the EPA's decision is pending, yet, at this time, he will be unable to generate revenue. Thus, the manufacturer may develop severe cash-flow problems, which may lead to bankruptcy.

Section 5's premanufacture notice requirement for new chemical substances does not apply to silicon, gallium arsenide, cadmium sulfide, or their oxidation products since they are, in fact, listed within the EPA's inventory of chemical substances.<sup>186</sup> Other semiconductor materials developed for solar cells in the future, however, may constitute new chemicals and, therefore, may be subject to the notice requirement.

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180. *Id.* § 2604(b)(2)(B)(i).

181. *Id.* § 2604(c).

182. *Id.* § 2602(9).

183. *Id.* § 2604(a)(2) (1976). The factors which the EPA must consider in the determination of significant new use include the projected volume of the chemical substance manufactured or processed, the type, form, magnitude, and duration of exposure related to the significant new use, and the reasonably anticipated manner and methods of manufacturing, processing, distribution in commerce, and disposal of the chemical substance related to the use. *Id.*

184. 44 Fed. Reg. 2,242 (1979); 44 Fed. Reg. 59,764 (1979); 45 Fed. Reg. 54,642 (1980); 45 Fed. Reg. 57,150 (1980).

185. See Gaynor, *supra* note 147, at 1167. It should be noted, however, that §§ 5(e) and 5(f) provide complex procedures which could result in substantial delays, restrictions, or prohibitions. For an in-depth treatment, see *id.*, at 1169.

186. 2 OFFICE OF TOXIC SUBSTANCES, U.S. ENVIRONMENTAL PROTECTION AGENCY, TOXIC SUBSTANCES CONTROL ACT CHEMICAL SUBSTANCE INVENTORY 324 (1979) (cadmium sulfide, cadmium sulfate, cadmium oxide); *id.* at 716 (gallium arsenide, gallium oxide); *id.* at 113 (arsenic trioxide); 3 OFFICE OF TOXIC SUBSTANCES, U.S. ENVIRONMENTAL PROTECTION AGENCY, TOXIC SUBSTANCES CONTROL ACT CHEMICAL SUBSTANCE INVENTORY 1400 (1979) (silicon).

Significant new use criteria have not yet been promulgated. In the event that the EPA does not possess sufficient information to predict the effect of a chemical substance on health or the environment, section 4 grants it the authority to require manufacturers or processors to conduct tests for the development of the necessary data.<sup>187</sup> There is a likelihood that such testing will be required of manufacturers of photovoltaic solar cells. In order to require testing the EPA must also find that either the manufacture or use of a chemical substance may present an unreasonable risk of injury to health or the environment,<sup>188</sup> or that the chemical substance will involve substantial human or environmental exposure.<sup>189</sup> Congress deliberately chose not to provide a definition of the term "unreasonable risk."<sup>190</sup> It felt that such a determination involved the consideration and balancing of a number of factors and thus was best left to the discretion of the EPA.<sup>191</sup>

In order to determine what constitutes an unreasonable risk under section 4, the EPA has developed an approach involving the consideration of three possibilities, which represent increasing levels of concern: first, the substance may present a hazard; second, if it is hazardous, it may also present a risk; third, the risk may be unreasonable.<sup>192</sup> Whether a substance presents a hazard is determined by the potential effect of the chemical substance on humans or the environment.<sup>193</sup> If a chemical substance is toxic, carcinogenic, mutagenic, teratogenic, or poses other undesirable effects, it is potentially harmful and is therefore hazardous. A determination that a substance or activity may be hazardous need not always be based on definitive scientific data.<sup>194</sup> Since section 4's applicability is premised on a lack of sufficient data, a determination of hazard potential under this section must invariably involve reasonable scientific assumptions.<sup>195</sup> Even so, there is sufficient information avail-

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187. 15 U.S.C. § 2603(a) (1976).

188. *Id.* § 2603(a)(1)(A)(i).

189. *Id.* § 2603(a)(1)(B)(i). Section 4(c) provides for a single exception to the testing requirement. In order to avoid unnecessary duplication of effort the EPA may, upon receipt of an application, grant an exemption to any person who would otherwise be required to perform tests. Such an exemption may only be granted if the chemical substance is equivalent to one for which data has already been submitted, or for which the data is in the process of being developed. The exempted person, however, may be required to provide fair and equitable reimbursement to the person who provided or is developing the requisite data. *Id.* § 2603(c).

190. H.R. REP. NO. 1341, *supra* note 149, at 13-14.

191. *Id.* at 14.

192. 45 Fed. Reg. 48,524, 48,528 (1980).

193. *See id.*

194. *Id.*

195. *Id.*

able concerning the materials used in solar cells to conclude that some are hazardous.<sup>196</sup>

Once a substance is determined to be hazardous, the EPA uses the term "risk" to include the exposure potential of that substance.<sup>197</sup> As a result, in order to present a risk, a substance must not only be hazardous, but must also involve a possibility of exposing humans or the environment to the substance. A substance may be highly hazardous, yet pose no risk because of the lack of exposure potential.<sup>198</sup> Since the semiconductor materials used in solar cells can enter the environment in several ways, those that are hazardous will likely be considered by the EPA to pose a risk.<sup>199</sup>

Whether a risk is unreasonable involves a judgment on the part of the EPA. That judgment requires a balancing of the probability of occurrence and the severity of harm versus the effects of regulatory action upon the benefits to society to be derived from the use of the substance.<sup>200</sup> Since only testing is required under section 4, the public does not lose any benefits.<sup>201</sup> Therefore, it is relatively easy for the balance to tip in favor of testing.

Section 4 also authorizes the EPA to require testing if the substance will be produced in substantial quantities or will result in a substantial exposure of humans or the environment, even if there is no suspicion that the substance is actually harmful.<sup>202</sup> In deciding whether to require testing, the EPA is not limited to a consideration of the sheer volume of production or the exposure at any particular point in time. The EPA may consider such factors as the duration of exposure, the level or severity of exposure, the number of people exposed or the extent of environmental exposure at various periods of time.<sup>203</sup>

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196. See text and notes at notes 103-31 *supra*.

197. 45 Fed. Reg. 48,524, 48,528 (1980).

198. There is usually an inverse relationship between hazard and exposure—the more severe the potential hazard, the less exposure is necessary to create a risk.

199. See text and notes at notes 132-35 *supra*.

200. 45 Fed. Reg. 48,524, 48,528 (1980).

201. In applying the balancing process the EPA need not include a formal cost-benefit analysis. H.R. REP. NO. 1341, *supra* note 149, at 14.

202. 15 U.S.C. § 2603(a)(1)(B)(i) (1976). In enacting this section, Congress realized that a "vast volume of chemicals have, [sic] for the most part, been released into the environment with little or no knowledge of their long-term health or environmental effects." H.R. REP. NO. 1341, *supra* note 149, at 3. Past practices have at times resulted in the widespread distribution and use of a chemical before its hazardous qualities were discovered, such as with asbestos, PCB's, vinyl chloride. *Id.* By providing the opportunity for the EPA to require testing of extensively used, insufficiently tested chemicals, Congress felt that the experiences of the past could be avoided. *Id.*

203. *Id.* at 18.

Two of the semiconductor materials used in solar cells—cadmium sulfide and gallium arsenide—are hazardous materials.<sup>204</sup> They also present a risk, since they may enter the environment.<sup>205</sup> Therefore, the EPA may determine that their use in photovoltaic solar collectors presents an unreasonable risk to health and the environment. Even if the EPA determines that the risk is not unreasonable, the possibility that solar cells could be widely used may result in a determination that the quantity involved is substantial enough to require testing.<sup>206</sup> In either case, however, before the EPA may require testing, it must also show that there is insufficient data available and that testing is necessary to provide that data.<sup>207</sup> Since some of the toxicological properties and environmental effects of these materials and their oxidation products are known,<sup>208</sup> the EPA may find this information sufficient to determine whether regulatory action under section 6 is necessary. If this information is not sufficient, testing of these substances may be required.<sup>209</sup> Such testing can involve both costs and delays. If testing were to be required, however, the costs could be shared, since both cadmium sulfide and gallium arsenide have numerous other commercial uses<sup>210</sup> and since their oxidation products occur as effluents of other industries.<sup>211</sup> If these costs were

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204. See text at note 196 *supra*.

205. See text at note 199 *supra*.

206. See text at note 202 *supra*.

207. *Id.* §§ 2603(a)(1)(A)(ii), 2603(a)(1)(A)(iii), 2603(a)(1)(B)(ii), 2603(a)(1)(B)(iii).

208. See text at notes 103-31 *supra*.

209. Even if existing data is not deemed insufficient, testing may be required if these substances are placed on a list of substances to be given priority testing. Section 4(e) establishes a federal interagency testing committee whose function is to make recommendations to the EPA of chemical substances and mixtures to which the EPA should give priority when requiring testing under section 4(a). The EPA may choose not to pursue a particular recommendation of the committee, but must state the reasons for its lack of action in the Federal Register. 15 U.S.C. § 2603(e)(1)(B) (1976). The EPA is not permitted merely to publish progress reports in lieu of reasons for not initiating section 4(a) rulemaking proceedings regarding chemicals designated by the interagency testing committee. *Natural Resources Defense Council, Inc. v. Costle*, 10 ENV'T L. REP. 20,274, 20,277 (S.D.N.Y. 1980).

210. Cadmium sulfide has been used as a pigment for glass, enamels, ceramics, rubber, plastics and paint. Nriagu, *Production Uses and Properties of Cadmium*, in *CADMIUM IN THE ENVIRONMENT* 62 (J. Nriagu ed. 1980). Gallium arsenide is widely used by the electronics industry in light-emitting diode displays, lasers, and transistors. C. GOOCH, *GALLIUM ARSENIDE LASERS* 1-4 (1969).

211. Cadmium oxide and cadmium sulfate are atmospheric effluents of the primary copper-, lead- and zinc-refining industries. Cadmium sulfide is frequently found with the ores of zinc and lead. R. COLEMAN, *SOURCES OF ATMOSPHERIC CADMIUM* 12, 35, 42 (1979) (EPA-450/5-79-006; PB 80-121221).

Arsenic trioxide is an atmospheric effluent of the primary copper-refining industry and of the arsenic refining industry. S. ARCHER, T. BLACKWOOD & T. CORWIN, *STATUS ASSESSMENT OF TOXIC CHEMICALS: ARSENIC* 2 (1979) (EPA-600/2-79-2106).

shared, the economic impact of a testing requirement on the photovoltaic industry would be reduced. Since the large-scale use of photovoltaics is not foreseen in the immediate future,<sup>212</sup> it is also possible that, by the time that solar collectors employing gallium arsenide or cadmium sulfide solar cells are placed in the environment, other sources will have already developed the requisite data. It would not be advisable, however, for the photovoltaic industry to wait for data to be developed by other sources, since the data should be used to plan the direction of research and development. By developing such data early, and suitably modifying the research strategy, the costs of abandoning a project because of the toxicity of the materials involved, after considerable sums of money have been expended on research and development, can be avoided.

While the information-gathering provisions of TSCA may have some economic impact on the development of photovoltaics, the effect is not likely to be significant since testing involves a one-time expense and the record-keeping provisions involve mostly clerical costs. Therefore, the costs incurred under those provisions do not warrant inclusion in feasibility studies for the technology. Instead, the major impact of the provisions just discussed will arise from the fact that they provide the basis for regulatory activities under sections 6<sup>213</sup> and 7<sup>214</sup> of TSCA.

#### b. Regulation of Activities

Once the EPA has obtained the necessary data, it is authorized to regulate the substances involved in a variety of ways. The information gathered under TSCA provides the EPA with a basis for evaluating the extent to which regulation is necessary in order to control the manufacture, use, and disposal of a chemical substance for the purpose of preventing an unreasonable risk of injury. Section 6, by providing for a wide range of regulatory restrictions, and section 7, establishing judicial remedies for imminent hazards, authorize a number of regulatory alternatives that the EPA may employ in order to accomplish this regulatory task in the least burdensome manner.

When the EPA finds that a chemical substance poses an unreasonable risk of injury to health and the environment, section 6 requires the EPA, using the least burdensome method, to impose one or more

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212. See note 15 *supra*.

213. 15 U.S.C. § 2605 (1976).

214. *Id.* § 2606.



of the following restrictions on activities associated with the chemical substance in order to protect against that risk:<sup>215</sup>

- a prohibition against the manufacture, processing, or distribution in commerce of the substance;<sup>216</sup>
- a limitation on the amount of the substance manufactured, processed, or distributed in commerce;<sup>217</sup>
- a prohibition against the manufacture, processing or distribution in commerce of the substance for a particular use, or for a particular use in excess of a specified concentration;<sup>218</sup>
- a limitation on the amount of the substance manufactured, processed, or distributed in commerce for a particular use, or a particular use in excess of a specified concentration;<sup>219</sup>
- a labeling requirement;<sup>220</sup>
- the retention of records and the testing or monitoring of the processes used;<sup>221</sup>
- a prohibition or regulation of the manner or method of commercial use;<sup>222</sup>
- a prohibition or regulation of the disposal of the substance;<sup>223</sup>
- individual and public notice by the manufacturer to persons in possession of the substance, of the risks of injury involved;<sup>224</sup>
- a repurchase or replacement of the substance by the manufacturer or processor.<sup>225</sup>

Furthermore, the EPA may impose quality control requirements on a manufacturer or processor in order to prevent the unintentional creation of an unreasonable risk of injury.<sup>226</sup> Thus, the EPA has wide authority to regulate the manufacture, distribution, use, and disposal of any substances that it determines pose an unreasonable risk.

Under section 7<sup>227</sup> the EPA has additional powers if the chemical substance presents such an imminent and unreasonable risk of seri-

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215. *Id.* § 2605(a).

216. *Id.* § 2605(a)(1)(A).

217. *Id.* § 2605(a)(1)(B).

218. *Id.* § 2605(a)(2)(A).

219. *Id.* § 2605(a)(2)(B).

220. *Id.* § 2605(a)(3).

221. *Id.* § 2605(a)(4).

222. *Id.* § 2605(a)(5). The distinction between "the manner or method of commercial use" as the term is used in this provision and a "particular use" as the term is used in sections 2605(a)(2)(A) and 2605(a)(2)(B), see text and notes at notes 218 and 219 *supra*, is illustrated in the following example: Painting constitutes a particular use, while spray painting or application with a brush constitute methods of use.

223. 15 U.S.C. § 2605(a)(6) (1976).

224. *Id.* §§ 2605(a)(7)(A) and (B).

225. *Id.* § 2605(a)(7)(C).

226. *Id.* § 2605(b).

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ous and widespread injury that a final rule under section 6 cannot be promulgated quickly enough to protect against the risk. Section 7 authorizes the EPA to bring suit in federal district court for an order allowing the seizure of the chemical substance and/or requiring the manufacturer to notify purchasers of the risks, to provide public notice of the risk, and to recall, replace, or repurchase the substance.<sup>228</sup> Since section 7 applies only when the danger posed by the chemical substance is both imminent and unreasonable, it is unlikely that this section will be applied to photovoltaic solar cells.

Unlike the determination made under section 4, a finding under section 6 that a substance presents an unreasonable risk may deny society the benefits of a substance because the EPA may restrict its use. For this reason, the balancing test is applied more carefully under section 6.<sup>229</sup> Congress chose to designate specific factors that the EPA must consider in the balancing of risks against benefits, and directed the EPA to publish its findings with respect to these factors.<sup>230</sup> As a result, the EPA must consider the magnitude and effect of the substance's exposure on human health and the environment, the benefits of the substance, the availability of substitutes, and the economic consequences, including effects on small business, technological innovation, health, and the environment. Using these findings, the EPA must determine whether a substance presents an unreasonable risk by identifying a hazard, assessing the risk posed by the hazard, and balancing the degree of harm possible from the risk against the benefits lost by not accepting the risk.<sup>231</sup>

Because the EPA's process of determining whether a substance poses an unreasonable risk is so complex and open-ended, it is impossible to predict how the EPA may decide to regulate the photovoltaic industry. Several conflicting considerations, however, are involved. Two semiconductor materials—gallium arsenide and cadmium sulfide—are hazardous because they are toxic and carcinogenic.<sup>232</sup> In

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228. *Id.* § 2606(b).

229. Congress intended that the unreasonable risk standard requiring testing under section 4 to be less stringent than the unreasonable risk standard for determining the extent of regulation to be imposed under section 6. H.R. REP. NO. 1341, *supra* note 149, at 14-15.

230. 15 U.S.C. § 2605(c)(1) (1976).

231. In *Environmental Defense Fund v. EPA*, No. 79-1580 slip op. (D.C. Cir. Oct. 30, 1980), the court had the opportunity to interpret the meaning of "unreasonable risk" as used in section 6 of TSCA. Acknowledging that TSCA does not define the term, the court looked to an earlier judicial interpretation of a similar provision contained in the Federal Hazardous Substances Act and concluded that the determination of unreasonable risk involves a balancing between "the severity of the injury that may result from the product, factored by the likelihood of the injury [and] the harm the regulation itself imposes upon manufacturers and consumers." *Id.*, slip op. at n.24, *quoting* *Forester v. Consumer Product Safety Comm'n*, 559 F.2d 774, 789 (D.C. Cir. 1977).

232. See text and notes at notes 110-11 and 118-20 *supra*.

addition, some of their byproducts also exhibit some evidence of mutagenicity and teratogenicity.<sup>233</sup> Since the highest risk from their use arises in the event of a fire at a decentralized photovoltaic facility,<sup>234</sup> the EPA could logically conclude that the use of gallium arsenide and cadmium sulfide solar cells in decentralized applications presents a risk of injury.

To determine if this risk represents an unreasonable risk, the EPA must perform the balancing test. Section 6 directs the EPA to balance the benefit of using gallium arsenide or cadmium sulfide in decentralized applications against the risk posed by the placement of these toxic substances in a location that may result in substantial harm to human health.<sup>235</sup> Decentralized applications, which place the photovoltaic materials in close proximity to the energy user, present the most environmentally attractive, energy-efficient use of solar energy.<sup>236</sup> Furthermore, gallium arsenide has properties that permit the fabrication of very efficient solar cells,<sup>237</sup> while cadmium sulfide solar cells can be manufactured inexpensively.<sup>238</sup> Such factors favor a determination that the risk is reasonable.

On the other hand, the EPA must consider the facts that centralized collectors reduce the dangers of exposing humans to the toxic materials and that another semiconductor material, silicon, presents no hazard either to health or the environment<sup>239</sup> and can serve in many applications as a substitute material. Depending on how it weighs these factors, the EPA may determine that gallium arsenide and cadmium sulfide solar cells, or certain of their applications, present an unreasonable risk of injury to health or the environment. If such a determination is made, the EPA may decide to invoke its extensive regulatory powers authorized by section 6.

Under section 6 the EPA has a number of regulatory options.<sup>240</sup> For example, it could prohibit outright the use of gallium arsenide or cadmium sulfide; or it could restrict their use to applications in remote locations, such as solar farms. The EPA could limit the amount of toxic material used in collectors placed on the roofs of buildings, or it could merely require warning labels. The economic

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233. See text and notes at notes 112-16 and 121-28 *supra*.

234. See text at note 134 *supra*.

235. 15 U.S.C. § 2605(c) (1976).

236. See text following note 92 *supra*.

237. See text and notes at notes 38-39 *supra*.

238. See text and notes at notes 30-32 and 40 *supra*.

239. See text and notes at notes 104-09 *supra*.

240. See text and notes at notes 216-26 *supra*.

burden placed on the photovoltaic industry by a regulatory action will necessarily vary with the option selected by the EPA. But if the possibility of the EPA's invoking some of the regulatory alternatives authorized by TSCA, such as an outright prohibition of the use of toxic materials in solar collectors or a requirement calling for the recall and repurchase of collectors containing toxic materials, is included in an economic analysis developed for photovoltaics, certain approaches to utilizing solar cells are likely to become more attractive than others. For example, developing solar cells made with thin films of nontoxic amorphous silicon for rooftop applications may present fewer long-term investment risks than cadmium sulfide solar cells. Moreover, if the use of cadmium sulfide or gallium arsenide is restricted to collectors located far from populated areas, their development may no longer be considered viable because they would be located too far from the energy user to permit use of the waste heat they also generate.<sup>241</sup> Such considerations could have a major impact on the direction of the development of the technology if considered early in the process.

The disposal of obsolete solar cells can potentially present a risk of injury to health and the environment. Unless regulations dictate otherwise, the methods used to dispose of obsolete solar cells will depend on the economic value of the solar cell materials.<sup>242</sup> To prevent the harm possible from improper disposal of solar cells containing toxic materials, the EPA may set disposal requirements such as requiring manufacturers to repurchase spent solar cells. The disposal requirements could increase the costs associated with solar cells fabricated from toxic materials relative to solar cells fabricated from silicon.

The regulatory provisions of section 6 and 7 grant the EPA a wide range of regulatory options having impacts on the technology ranging from minimal to significant. Similarly, the economic effects of action under sections 6 and 7 can range from minimal to severe. The

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241. Studies have shown that unless the thermal energy can be used profitably, centralized power stations using centralized light collectors will not be cost-competitive with fossil fuel-generated power in the near future. Leonard, *Central Station Power Plant Applications for Photovoltaic Solar Energy Conversion*, in THE CONFERENCE RECORD OF THE THIRTEENTH IEEE PHOTOVOLTAIC SPECIALISTS CONFERENCE—1978 at 1190.

242. Gallium arsenide is relatively expensive, costing about \$3 per gram. CRC, *supra* note 117, at B-17. Since gallium arsenide solar cells are fabricated from wafers, and therefore can easily be separated from the collector, a market for scrap gallium arsenide solar cells can be expected to develop. Cadmium sulfide solar cells are generally thin films and the cadmium sulfide cannot be easily extracted. Furthermore, the price of cadmium is only about \$4.40 per kilogram. The Northern Miner, Feb. 19, 1981, p. 13, col. 1. Thus, in all probability cadmium sulfide cells will be discarded and not recycled.

fact that regulatory action is probable, however, should be factored into the economic analyses. Only after this probability of regulatory action is factored into the economic analyses of technologies based on toxic materials can a true economic comparison with technologies based on silicon, which is not likely to be regulated, be made.

### *B. Other Environmental Statutes*

Other environmental statutes, such as the National Environmental Policy Act (NEPA), the Clean Water Act, or the Clean Air Act, may introduce regulatory control of photovoltaics. Although these statutes are not examined in this article, they may substantially affect the economic costs of solar photovoltaic energy. For example, NEPA may require the preparation of an environmental impact statement, a cost that could arise each time a centralized generating facility is to be built. The Clean Water Act may require treatment facilities for water runoff from the photovoltaic panels located at a centralized facility. Compliance with the Clean Air Act may increase the cost of energy storage devices. For example, desalination of brine in order to make water suitable for hydrogen production yields a salt residue.<sup>243</sup> This residue may have to be covered or removed in order to prevent the wind from dispersing the salt and thus causing an air pollution problem. Compliance with each of these statutes may increase the final cost of energy produced by photovoltaic solar cells. The consideration of the economic effects of these statutes, through a process similar to the one presented in this article for the case of TSCA, will provide a needed basis for arriving at the potential monetary costs that could be incurred as a result of the regulation of the photovoltaic solar cell industry.

In this article, only statutes at the national level have been discussed. The potential economic effects of state and local statutes should not be ignored or underestimated in final cost analyses. Their effects may extend well beyond local boundaries, as the recent action by Massachusetts regarding urea formaldehyde foam insulation indicates.<sup>244</sup> After the installation of this type of insulation in many homes, it was discovered that the insulation permeated the home with noxious fumes.<sup>245</sup> Responding to numerous consumer com-

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243. See text and notes at notes 98-100 *supra*.

244. Wall Street Journal, July 14, 1980, at 17, col. 4. Urea formaldehyde foam insulation became widely used after the 1973 Arab oil embargo. The Department of Energy has rated it as the most effective blown insulation available to homeowners, and it has been installed in about 600,000 homes nationwide, 11,000 in Massachusetts. *Id.*

245. *Id.*

plaints, Massachusetts first banned the use of urea foam insulation within the state and then followed with a requirement that manufacturers pay for the removal of the foam from the homes.<sup>246</sup> The estimated cost of removal is formidable, \$20,000 per home, and, if the Massachusetts action withstands a \$500 million lawsuit by the manufacturers, it could cause the bankruptcy of most of the urea foam manufacturers in the United States.<sup>247</sup> Similar state action affecting rooftop photovoltaic solar collectors containing toxic semiconductors could, for example, evolve from a concern for the safety of firefighters. Should the photovoltaic industry be required to remove or repurchase such solar panels, the economic ramifications would be disastrous.

Increased regulatory control of photovoltaics may also result from a widely publicized mishap, such as a major fire at a centralized photovoltaic facility resulting in the release of large quantities of toxic materials.<sup>248</sup> The ensuing public outcry and concern over the resultant environmental and health damages could be similar to that evoked by the incidents at Three Mile Island<sup>249</sup> and Love Canal.<sup>250</sup> Should a disaster involving photovoltaics occur, legislation directed at preventing future disasters could impose extreme economic burdens on the photovoltaic industry. Therefore, it would be economically and politically prudent for the industry to examine areas of potential disaster in order to minimize or eliminate them through design choice.

Anticipation of regulatory action through farsighted design choice at the outset can result in significant economic savings for both the consumer and the manufacturer. Since the photovoltaic industry is still in the developmental stages it can take advantage of its situation by incorporating environmental factors into its design development

246. *Id.*

247. *Id.*

248. See text at note 134 *supra*.

249. The future of nuclear power may well depend on the public opinion following the accident at the Three Mile Island nuclear reactor on March 28, 1979. For a thorough discussion of both the technical and political issues raised by that accident, see IEEE SPECTRUM, Nov., 1979 (special issue: Three Mile Island and the Future of Nuclear Power).

250. The Hooker Chemical Company used the Love Canal Waste Landfill in Niagara Falls, New York, as a chemical dumpsite from 1942 to 1953. In 1976, years after Hooker had sold the property, massive quantities of hazardous chemicals began to appear at the surface and seep into the basements of homes in the area. The resultant publicity over the property and health damage created an awareness in the American public of the seriousness of the hazardous waste problem. For an in-depth review of the Love Canal disaster, see *Jt. Hearings Before the Subcomm. on Environmental Pollution and Resource Protection of the Senate Comm. on Environment and Public Works, Hazardous and Toxic Waste Disposal*, 96th Cong., 1st Sess. (1979).

process, thereby reducing or eliminating future compliance costs. Compliance with environmental regulations passed after the production process has been set and the product introduced into the market can be expensive, as has been shown by the automotive industry. Estimates of the cost of complying with emissions standards brought about by the Clean Air Act ranged from \$200<sup>251</sup> to \$565<sup>252</sup> per vehicle for 1979. Furthermore, in 1979 consumers had to spend, on the average, an additional \$41 per vehicle in order to purchase the unleaded gasoline necessitated by the pollution control devices.<sup>253</sup> It is reasonable to expect, that had regulatory control been anticipated by the automotive industry, costs could have been reduced by originally designing cleaner burning engines rather than using the less efficient process of retrofitting existing engine designs with emission control devices. The photovoltaic industry can, by anticipating regulatory control making the appropriate design choices, avoid expensive manufacturing process changes after regulatory control is instituted.

#### IV. CONCLUSION

Photovoltaic solar cells convert sunlight directly into electricity and therefore represent an attractive method of utilizing the energy present in sunlight. Although this method of electricity production is generally considered to be an environmentally benign alternative to the consumption of fossil fuels, nevertheless there are potentially significant costs associated with its environmental effects. In the past these costs have been omitted from the economic analyses that help to determine the future direction of photovoltaic research. An examination of one area of environmental concern—the dangers posed by the toxic properties of some of the semiconductor materials used in solar cells—suggests that the adverse environmental and health effects of photovoltaics can affect the economic cost analyses for photovoltaics in two ways. First, they may result in direct environmental damage, the price of which is borne by the general public or, if liability is established, by the manufacturer. Second, there are costs incurred by compliance with the regulatory scheme

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251. Wakefield, *The Regulated Automobile, Part I: Emissions and Noise Regulations*, ROAD AND TRACK, Apr., 1980, at 176.

252. *Hard Times Come to Environmentalists*, U.S. NEWS AND WORLD REPORT, March 10, 1980, at 49.

253. In 1979 the average passenger vehicle travelled 10,046 miles, 72 NAT'L PETROLEUM NEWS 88 (1980) (Factbook Issue No. 6A), consuming 715 gallons of gasoline, *id.*, at an average price of \$0.865 per gallon for leaded regular and \$0.922 per gallon for unleaded regular at full service stations, *id.* at 101.

imposed by TSCA, under which the regulation of photovoltaics is likely. The economic impact of the Act will depend upon which regulatory alternative the EPA will chose.

The environmental costs associated with the toxicity of photovoltaic materials are just one example of a variety of costs, associated both with direct environmental harm and with regulation under environmental statutes, that ought to be considered in evaluating the desirability of the nascent photovoltaic technology. It is essential that these environmental costs be included in economic cost analyses, since their omission will bias the analyses in favor of a technology that, in the long run, may prove to be more expensive than other alternatives. While photovoltaics may well be the technology of the future, the technology should be implemented only after all of its costs have been considered. A consideration of environmental effects and costs at the outset will allow their minimization through proper design choice and will help to avoid the unpleasant and environmentally expensive belated discoveries made by other industries.